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MEDICAL EVACUATION AND TREATMENT CAPABILITIES OPTIMIZATION MODEL (METCOM)

by

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September 2005

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GLOSSARY OF TERMS

AMAL	Authorized Medical Allowance List
AO	Area of Operations
AOR	Area of Responsibility
BAS	Battalion Aid Station
BES	Beach Evacuation Station
BPSP	Balanced Priority Sub-Policy
CBRNE	Chemical, Biological, Radiological, Nuclear, Explosive
CBTZ	Combat Zone
CJCS	Chairman of the Joint Chiefs of Staff
COA	Course of Action
COCOM	Combatant Commander
COMMZ	Communications Zone
CompTre	Complete Treatment
CONUS	Continental United States
CRTS	Casualty Receiving and Treatment Ship
DIS	Diseased
DoD	Department of Defense
DOW	Died of Wounds
EMF	Expeditionary Medical Facility
EMU	Expeditionary Medical Unit
EPP	Evacuation Priority Policy
EPW	Enemy Prisoner of War

ESP	Estimating Supplies Program
EvaCapG	Evacuation Capacity General
EvaCapS	Evacuation Capacity Special
EvaPri	Evacuation Priority
FHP	Force Health Protection
FMF	Fleet Marine Force
FRSS	Forward Resuscitative Surgery System
FSSG	Force Service Support Group
GAO	Government Accounting Office
GenTre	General Treatment
GPSP	General Priority Sub-Policy
HNS	Host Nations Support
HSS	Health Service Support
ICU	Intensive Care Unit
JFS	Joint Force Surgeon
JTS	Joint Theater Surgeon
KTO	Kuwaiti Theater of Operations
LHD	Amphibious Assault Ship
LOC	Level of Care
LPX-MED	External Logistics Processor-Medical Module
MASF	Mobile Aeromedical Staging Facility
MAT	Medical Analysis Tool
MEDEVAC	Medical Evacuation
MEPES	Medical Planning and Execution System

METCOM	Medical Evacuation and Treatment Capabilities Optimization Model
METS	Medical Evacuation and Treatment System
MO	Medical Officer
MOE	Measure of Effectiveness
MP	Military Police
MRE	Medical Requirements Estimator
M&S	Modeling and Simulation
MPM	Medical Planning Module
MTF	Medical Treatment Facility
NATO	North Atlantic Treaty Organization
NBI	Non-Battle Injury
NEO	Non-Combatant Evacuation Operation
NHRC	Naval Health and Research Center
NonTre	Non-Treated
OCONUS	Outside the Continental United States
OEF	Operation Enduring Freedom
OIF	Operation Iraqi Freedom
OPLAN	Operation Plan
OPTEVAC	Optimal Placement of Casualty Evacuation Assets
OR	Operating Room
PAR	Population at Risk
PC	Patient Condition
PMI	Patient Movement Item

POI	Point of Injury
PPP	Primary Priority Policy
PSP	Priority Sub-Policy
RE	Requirements Estimator
RP	Retained Personnel
RTD	Return to Duty
SECDEF	Secretary of Defense
SpecTre	Specialty Treatment
STANAG	Standardization Agreement (NATO)
STP	Shock Trauma Platoon
T-AH	Hospital Ship
TML+	Tactical Medical Logistics Planning Tool
TPFDD	Time-Phased Force Deployment Data
TPP	Treatment Priority Policy
TreCapG	Treatment Capacity General
TreCapS	Treatment Capacity Special
TriCat	Triage Category
WIA	Wounded in Action

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Nothing epitomizes the essence of the military health service support (HSS) system better than the reverberating call of "*Corpsman Up*!" that has resonated across battlefields throughout American history. This thesis is dedicated to those that have stood the watch, always present and always ready, to answer the call in constant support of the warfighters' needs, the military health system (MHS), and all that serve our country.

NAVY MEDICINE
World Class Care…Anytime, Anywhere

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A Corpsman's Prayer

Grant me, oh Lord, for the coming events;
Enough knowledge to cope and some plain common sense.
Be at our side on those nightly patrols;
And be merciful judging our vulnerable souls.
Make my hands steady and as sure as a rock;
when the others go down with a wound or in shock.
Let me be close, when they bleed in the mud;
With a tourniquet handy to save precious blood.
Here in the jungle, the enemy near;

Even the corpsman can't offer much lightness and cheer.
Just help me, oh Lord, to save lives when I can;
Because even out there is merit in man.
If It's Your will, make casualties light;
And don't let any die in the murderous night.
These are my friends I'm trying to save;
They are frightened at times, but You know they are brave.
Let me not fail when they need so much;
But to help me serve with a compassionate touch.
Lord, I'm no hero -- my job is to heal;
And I want You to know Just how helpless I feel.
Bring us back safely to camp with dawn;
For too many of us are already gone.
Lord bless my friends If that's part of your plan;
And go with us tonight, when we go out again.
-Author Unknown

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EXECUTIVE SUMMARY

Operational planning and policy for Navy medicine has evolved over the past century from a predominantly large-scale, land-based, fixed facility platform into a more robust, compact, mobile, and forward deployed continuum of care capable of projecting casualty care directly within the combat zone as well as evacuating the injured expeditiously rearward when more definitive care is warranted. This dynamic evolution in structure and mission of medical platforms has created greater needs for effective policy and planning tools that integrate resource requirements, project expected patient casualty demands upon the medical system, and validate appropriate staffing and structure to provide and sustain the highest levels of medical care from time of injury until receipt of definitive care.

In this thesis we develop a new model called Medical Evacuation and Treatment Capabilities Optimization Model (METCOM) that's designed as a user friendly optimization model that augments current simulations and assists in optimizing efficiencies, allowing for redistribution, restructuring, or realignment of medical resources and materials to better meet requirements elsewhere. The model builds upon this revolution of change in military medical care by addressing variations in capabilities and policies of the medical evacuation and treatment system (METS) in order to discern effects on desired medical outcomes.

To achieve this end-state, a combination of multiperiod descriptive and prescriptive models were utilized in order to provide medical planners and decision makers with the flexibility to employ a broad range of scenarios that could be analyzed for results against key measures of effectiveness (MOEs). In fact, these operational scenarios as represented through the utilization of different casualty inflow distributions were shown to elicit unique and measurable outcomes for each of the overflow queues generated within the METCOM network. While no specific policy stood out above the rest for every scenario, there were distinct advantages and disadvantages in utilizing some policies as they related to specific casualties as prioritized by a medical and evacuation priority indices.

Additionally, METCOM addresses the cost associated with delivery of care and evacuation, allowing again for decision makers to meet all requirements at the minimal cost. Through the use of the cost optimization model within METCOM it was displayed that costs could be reduced from the default METS setup thru the optimization (reduction) in necessity for unused medical and evacuation capacities. This resulted in a METS structure that operated with the lowest resource utilization costs while within all MOE constraints.

Taken together, the descriptive and optimization data that METCOM provides can be utilized by planners and decision makers to employ appropriate policies, insert necessary medical and evacuation capabilities within the theater of operations, and economize the cost so that unneeded resources may allocated elsewhere.

I. INTRODUCTION

"The great thing in all military service is health"
- Admiral the Lord Nelson[1]

A. BACKGROUND

Operational planning and policy for Navy medicine has evolved over the past century from a predominantly large-scale, land-based, fixed facility platform into a more robust, compact, mobile, and forward deployed continuum of care capable of projecting casualty care directly within the combat zone as well as evacuating the injured expeditiously rearward when more definitive care is warranted. This dynamic evolution in structure and mission of medical platforms has created greater needs for effective policy and planning tools that integrate resource requirements, project expected patient casualty demands upon the medical system, and validate appropriate staffing and structure to provide and sustain the highest levels of medical care from time of injury until receipt of definitive care.

In this thesis we develop a new model called Medical Evacuation and Treatment Capabilities Optimization Model (METCOM) that's designed as a user friendly optimization model that augments current simulations and assists in optimizing efficiencies, allowing for redistribution, restructuring, or realignment of medical resources and materials to better meet requirements elsewhere. The model builds upon this revolution of change in military medical care by addressing variations in capabilities and policies of the medical evacuation and treatment system (METS) in order to discern effects on desired medical outcomes. To achieve this end-state, a combination of descriptive and prescriptive models were utilized in order to provide medical planners and decision makers with the flexibility to employ a broad range of scenarios that could be analyzed for results against key measures of effectiveness (MOEs).

First we address the complexities that specific medical and evacuation policies have upon key metrics by employing a descriptive multi-period network representing the

[1] Letter to Dr. Mosely 1803. Cited by R. D. Heinl Jr. in *A Dictionary of Military and Naval Quotations*. Naval Institute Press, 1966.

structural architecture of the METS. Casualty flow was modeled throughout the network whereby different policies could be comparatively measured for effectiveness over any given combat scenario. This component of the model allows for decision makers to understand the bottom-line effectiveness of specific treatment and evacuation policies given their determined capacities and medical requirements.

The second component of the model addresses the optimal usage of constrained resources by minimizing the cost associated with the medical and evacuation capacity requirements of the METS while maintaining pre-defined metrics such as waiting (queue time) for delivery of care or evacuation that denotes the desired level of care being delivered. Here a decision maker can choose the medical risk they wish to associate with a given operation by setting maximum limits to specific metrics and allowing the model to define the optimal treatment and evacuation capacities necessary to obtain that specified level of care.

Taken together the components form a formidable model that identifies best operational policy and capacity within the METS for any given combat scenario. This can also greatly assist decision makers' operational and tactical decisions as it identifies bounds upon capabilities, thereby allowing for selection of a feasible solution from within the acceptable risk tolerance. Medical capacity and policy decisions also affect the processing of overall strategic planning due to their inherent interdependence with the capabilities of other warfighting objectives. Therefore, the ability to enumerate both the optimal and a "feasible set" of operational capabilities maximizes the flexibility of decision makers.

As previously stated, trends in warfighting doctrine have continued along the lines of emphasizing lighter, faster, forward extended operations requiring a parallel in transformation for medical services. This is epitomized in the Navy Medicine motto change from Charlie-Golf-One, which means "standing by ready to assist" to Charlie-Papa, "steaming to assist" (Cowan, 2003). These changes have led to the development of numerous new medical initiatives such as the Forward Resuscitative Surgery System (FRSS), Expeditionary Medical Unit (EMU), and the Shock Trauma Platoon (STP) that due to their innate structures of small scale, flexible assets, mobility, and swift response

capabilities are able to provide significant surgical stabilization efforts far forward in the area of operations (AO). However, as Tropeano (2003) states, "Introducing this new capability into the Marine Corps continuum of care has raised many questions as to its impact on medical treatment and resources." Thus, while individual medical platforms present specific capabilities, it is the integration of these assets into the functioning medical network within the theater of operations that must be accurately staffed, supported, and networked to ensure that the highest levels of continuum of care and optimal usage of resources are realized. Only then can valid and reliable assessment of the treatment and evacuation capacities ensure that casualties are expeditiously handled while loss of life and limb is minimized through the optimal use of these constrained resources.

Recent conflicts have provided an abundance of lessons learned and supported the necessity of changes within the organization and delivery of casualty care. As noted by Sundstrom, Blood, & Matheny (1996), "While casualties were relatively few in the Gulf Conflict [1991], and the wounded personnel did receive needed treatment in a timely fashion, future operations may yield larger numbers of casualties with greater potential for overwhelming the casualty evacuation system." Numerous studies (DoD, 1993; Endoso, 1994; Liston, 1998; Smith, 1995) indicated that had the medical system during Desert Shield/Desert Storm been taxed at its actual potential levels, serious shortages would have incurred with both evacuation and logistics assets, causing a detrimental blow to the levels of care provided. Particularly with the potential threat of chemical, biological, radiological, nuclear, and explosive (CBRNE) weapons to cause mass casualties, the ability for the efficient medical treatment and evacuation of a broad spectrum of casualties intra and inter-theater is paramount in preserving the required level of care conditionally accepted by the combatant commander.

Even without CBRNE concerns, patient flows traditionally ebb and tide with the intensity of conflict that commonly creates a non-uniform arrival rate of casualties. During the 1991 Gulf War within the Kuwaiti Theater of Operations (KTO), sixty-five percent of USMC admissions received at regional Level II facilities (e.g., STP or FRSS) occurred during the first week of major combat operations alone (Leedham and Blood, 1992). Additionally, during the KTO, treatment facilities were at greater distances from

the direct combat zone than warranted in current conflicts (Sundstrom, Blood, Matheny, 1996). Thus, as medical units move further forward in the theater of operations they can expect swifter arrival rates of casualties being routed to them with minimal delays due to their locality in the battlespace. Given a scenario with multiple casualties, a rapid arrival time cycle has the potential to overwhelm a MTF if it is not operating in an efficient manner or staffed with appropriate resources. Additionally, inappropriate structure of the medical system or inefficient delivery of treatment and evacuation can swiftly compound into unacceptable conditions. For example, during combat operations in the Gulf War of 1991, about 60 percent of patients ended up in the wrong destinations and half in the wrong country (Endoso, 1994). A GAO review (1996), also found that medical units were not staffed and equipped to provide noncombatant care and "Were unable to support evacuation of casualties from the combat theater or receive large numbers of chemically contaminated patients." Thus reiterating, while individual medical platform capabilities are essential, it is the optimal structure (staff, capabilities, capacities, etc.) and utilization combined with efficient integration of these assets that make a medical evacuation and treatment system capable of overcoming complications caused by the "fog of war".

It is paramount to have planning tools that appropriately identify and model the required demands and potential deficiencies within the health service support system. Early attempts at such included the medical simulation models Optimal Placement of Casualty Evacuation Assets (OPTEVAC), Medical Planning and Execution System (MEPES), and similar yet smaller linear program models that were developed in an attempt to forecast patient casualty flow requirements for supporting medical logistics (Levy, May and Grogan 1996a, 1996b; Matheny et al., 1998; Sundstrom, Blood and Matheny, 1996) The most viable of these simulation models were the External Logistics Processor-Medical Module (LPX-MED) and Medical Planning Module (MPM), with the latter being the only DoD approved tool for medical planning and programming. Both were developed as first steps toward joint medical operations planning and were influential precursors to current medical simulation models (Levy, May, Grogan, 1996). Presently the Joint Chief of Staff (JCS) J4 staff utilizes the Medical Analysis Tool (MAT), which synthesizes the previous MPM algorithms into the role of a Requirements Estimator (RE) and LPX-MED into a Course of Action Analysis (COAA). This is

augmented by the use of the Tactical Medical Logistics Planning Tool (TML+) developed by the Naval Health and Research Center (NHRC) for better analysis and accommodation of certain medical logistic materials. TML+ is a high-resolution model that is inclusive of all medical echelons of care, but maintains primary focus on the immediate treatment capabilities (Level I & II). TML+ also incorporates the Estimating Supplies Program (ESP), allowing the model to more effectively addresses required medical logistics to support different scenarios and the Authorized Medical Allowance List (AMAL) which consists of items of packaged medical supply blocks prepared for prescribed medical missions. MAT, which models at lower resolution than TML+ includes higher levels of care, but primarily focuses on intra-theatre evacuations with admissions being first recognized in the medical system upon reporting to Level II facilities. Both models are inherently dependent upon the Navy Line community for all inputs that ultimately create the expected casualty rates and medical logistic requirements.

The innate weakness of these simulations is that while they produce requirements and identify whether assets accommodate projected patient flows, they do not fully optimize the use of the medical logistics structure. Current medical simulations are limited to single scenario application each time they are run, which limits the ability to apply them to the dynamic and multidimensional environments experienced in real-world military operations. In effect, the simulations analyze single decision points within a controlled environment in which structural and operational variables are statically set in advance. Therefore, simulations are good at identifying “what if” values for pre-selected measures of effectiveness (MOEs) within single performance runs that present clear and concise reports, but lack the ability to produce a “big picture” of multiple dynamic decision points. Additionally, simulations introduce a certain level of prohibitive functionality as they may be denied exploring other areas of the decision space due to time, costs, and intensive requirements for data required by multiple simulation scenario runs. Most importantly, while simulation modeling is adequate to identify requirements and deficiencies to meet requirements they do not appropriately address inefficiencies caused by potential underutilization of the medical system.

B. HEALTH SERVICE SUPPORT (HSS) SYSTEM

In order to begin modeling the METS, a strong foundational knowledge of the current structure, modus operandi, and objectives of the HSS is necessary. The HSS system is a process that delivers on demand to the warfighter a healthy, fit, and medically ready force; counters the health threat to the deployed force; and provides critical care and management for combat casualties (MCWP 4-11.1, 1998). It is an instrumental portion of the operational success to any mission and is commonly influenced by a plethora of factors as exhibited in Figure 1.1. It is unique in that it functions in a supportive role to the traditional logistics processes, and yet it is vital enough to be a decisive factor on the battle field. With appropriate medical treatment and evacuation of sick and wounded, the HSS system effectively allows the combatant commander (COCOM) to sustain the level of operations required for the duration of the conflict. Injuries to the warfighters represent the potential for reduced operational capability due to both the loss of physical manpower but also due to the psychological toll the sick and injured represent to their own units. As Kress (2000) states, "Because of the moral commitment to preserve human life, and the considerable attention that modern armies devote to preserve the welfare of their warfighters, medical treatment and evacuation is considered a major OpLog mission despite its small operational impact on the current campaign, and its relatively small scale." In the past, the infrastructure of the HSS has been large, cumbersome, and logistically intensive medical facilities far removed from the area of operations (AO).

However, as described previously, the HSS system has been revamped towards the objectives of the National Military Strategy which emphasizes the use of forward presence, power projection, and decreased footprint in theater. According to GAO reports (1996), "The Joint Staff recommended that the services investigate the possibility of evacuating casualties more quickly to the United States for treatment." This in fact was evidenced in action during the OIF/OEF conflict in which average time to transport casualties from the combat zone to the U.S. shrank from 8 days at the beginning of the conflict to less than 4 days by the end of 2004 (Gawande, 2004). The HSS now provides a more modular, smaller, far-forward surgical presence that allows for increased surgical capability as well as rapid evacuation (MCWP 4-11.1, 1998).

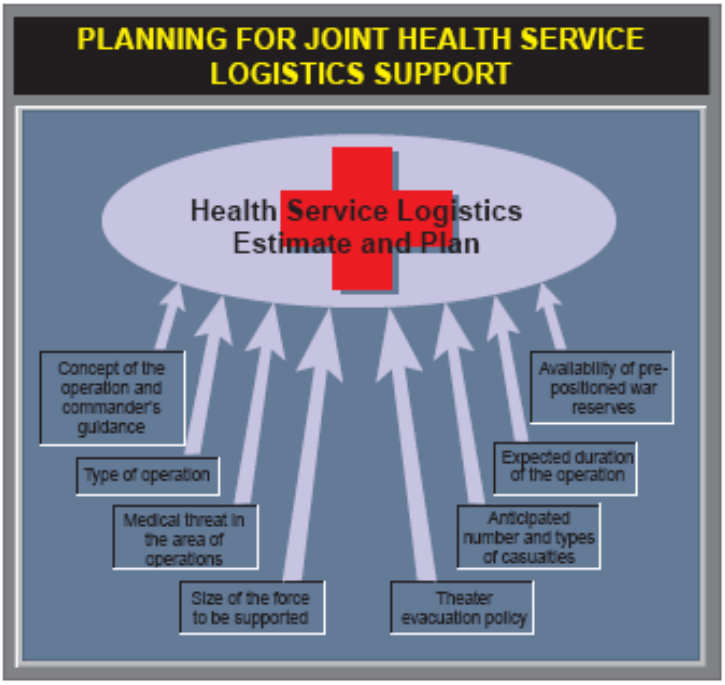

Figure 1.1 Medical Logistic Influencers (From JP 4-02.1, 1997)

The primary mission of the HSS is to preserve the life and limb of the warfighters. To meet this objective, the METS is focused on meeting the "Golden Hour" rule which dictates that if medical treatment can be provided within the first hour from point of injury (POI) the likelihood of saving life and limb is significantly increased (Wick et. al, 1998). Traditionally large immobile medical units far away from the combat area work against this time constraint of the "Golden Hour" and thus the services have shifted towards developing lighter and more mobile medical units that can reach casualties quicker or be more forward deployed in the battlespace. However, in developing more mobile units a trade-off occurs as overall capacity to treat casualties decreases and evacuation assets are reduced or incur additional limitations. This in effect is a tradeoff between the on-sight medical treatment capabilities and the evacuation efficiencies.

The tenet of the HSS system is the triad goal of providing the Right service, in the Right place, at the Right time (NTTP 4-02.2). A system is considered successful based upon its responsiveness, efficiency, and ability to save lives while returning maximum number of personnel back to duty. This objective is most readily met by executing a METS policy that aligns best with the strategic and operational plans for conflict. The

past HSS concept of providing definitive care in theater to maximize returned to duty (RTD) status has evolved to a concept that provides essential care in theater to either RTD within the theater patient movement policy or stabilize for patient movement to the next level of care, with enhanced en route medical care and definitive care (JP 4-02, 2001). However, the treatment and evacuation portions of the HSS system are at times diametrically opposed to the traditional logistics flow in the following major areas:

- Unlike the forward flow of supplies, patients are "going against the grain" as they are pushed rearward out of the combat zone. This can significantly impact areas of security, materiel and personnel availability, and operational ability. That is to say, every vehicle or air asset utilized to conduct medical evacuations is not available to provide further forward support in the form of weaponry, logistic re-supply, or even personnel re-supply.
- Rather than dealing with supplies measured in thousands of tons or cubic feet of materiel, the METS normally deals with (in relative terms) much smaller volumes and capacities.
- The METS is much more complex to plan for as arrivals of casualties may not always conform to a standard distribution. Utilization of the METS must be as consistent with minimal flow of patients as it must be in dealing with a mass casualty incident.
- Unlike most logistic support setups, it is common that no dedicated evacuation assets are assigned to most MTFs. Thus the system must many times operate on the contingency of availability of either a designated asset or lift of opportunity.
- Baseline, METS is dealing with people, not parts. Thus, a human factor enters the mix, causing both physical constraints on the logistic flow and operation of the METS network, but also adds an ethical, emotional, and psychological facet to the execution of the network.

- Delays or redirection of casualties may be prohibited as they must be delivered to the MTF with capabilities to treat their condition and too much delay can cause unacceptable degradation of the casualty's condition.

1. HSS Principles

The HSS system operates on the same principles of general logistics; responsiveness, simplicity, flexibility, economy, attainability, sustainability, and survivability. Unlike the general logistics function, the HSS has an added principle that must also ensure a continuity of care exists for all patients (NTTP 4-02.2, 2001). As Kress (2000) states, "Medical support during a campaign is a unique logistics function with respect to its effect on combat activities, its scale and its characteristics." Leaving a pallet of equipment unattended may be an acceptable practice for materiel purposes, but the same cannot be said for a human casualty who must always be attended and monitored.

These principles are guides for planning, organizing, managing, and executing service support function of the operational plan(s). They are situation dependent and seldom will all principles exert equal influence. However, identifying which ones have priority is essential to establishing an effective HSS. Service doctrine (JP 4-02, 2001; MCWP 4-11.1, 1998; NWP 4-02, 1995), define the principles and their relationships as exhibited below and in Figure 1.2.

Responsiveness: Responsiveness is the core metric amongst the current joint staff planners. It emphasizes that the medical plan must weigh the benefits of providing support as close to combat operations as possible with the limitations of care that can be provided in this environment. All else is irrelevant if the logistics and casualty support system cannot provide support, conform to, and complement the commander's concept of operations (NWP 4-02, 1995). The application of this principle has been the utilization of the tiered structure of MTFs into levels of care (LOCs) that focus on an objective of providing care within the "Golden Hour". Throughout history, this practice has contributed to the reduction in morbidity and mortality by placing HSS closer to where an injury or illness occurs (NWP 4-02, 1995).

Flexibility: Similar to the old cliché "The only thing constant is change", the HSS must be structured and functionally capable of extensive adaptation to changes in mission or operations. Emphasis is placed on retaining the capability to meet the demands of a spectrum of health services plans and operations while maintaining the same level of care. Flexibility in HSS planning operations complements the principles of responsiveness and economy.

Continuity: Once a casualty has entered the HSS system it is paramount that the METS provide optimum, uninterrupted care and treatment to the wounded, injured, and sick. This is a complex and sometimes difficult necessity as it requires vast integration of the medical treatment module and the evacuation module so as a casualty's treatment never exacerbates or falls below the level of treatment already started. Once care is initiated, it is continued whether the patient is in an MTF or in the casualty evacuation chain. The continuum of care provides the structure to achieve continuity and attain the principles of flexibility, economy, and sustainability (NWP 4-02, 1995).

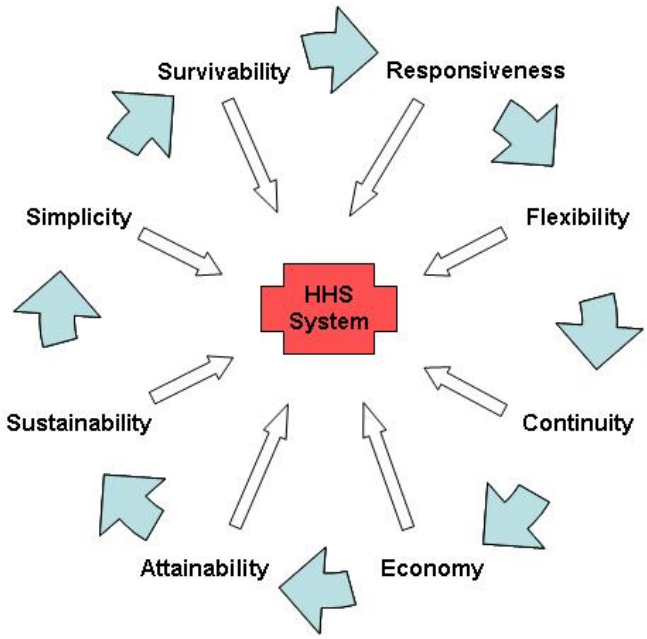

Figure 1.2 Principles of the Health Service Support system

Economy: Economy is driven by the existence of finite resources and requires the provision of support with the lowest possible investment of resources necessary to

accomplish the assigned mission. Thus, a balance within an economy of scales must be met as the size and structure of the HSS system will significantly impact the logistic, combat, and resource costs associated with providing a specific level of care. Economy in HSS has traditionally been accomplished by consolidating resources and facilities at the earliest practicable time. Although this practice produces economies in manpower and materiel, flexibility is frequently sacrificed. Economy through consolidation must balance with the need for diversified treatment as a defensive measure to ensure survivability (NWP 4-02, 1995).

Attainability: The ability to provide the minimum essential supplies and services required to begin combat operations. Initial battle casualties may require rapid movement through several levels of medical care to reach the level of treatment required. It is paramount that policies and HSS structure are developed around realistic and fully executable operational plans.

Sustainability: Sustainability is the ability to maintain a specified level of care throughout the operation. The principle of sustainability focuses attention on the long-term objectives and requirements of the supported force or unit. Sustainability in health service is attained by providing as complete an array of HSS within the operations area and within the theater, as necessary (NWP 4-02, 1995). Sustainability requires some degree of redundancy which may reduce attempts to practice economy. Sustainability demands austerity and conservation to preclude supply waste and shortages, and requires control measures and flexibility.

Simplicity: The avoidance of complex requirements, organizational structure, and operational procedures removes restrictions upon the other HSS principles. It fosters efficiency in both the planning and execution of HSS operations.

Survivability: Survivability is the capability to continue treatment and evacuation within the full spectrum of combat operations even when facing potential detrimental or destructive forces.

The COCOM and Joint Force Surgeon (JFS) may choose to improve certain areas dependent upon the present or projected combat operations. However, the dependency of these principles on one another emphasizes the reality that improving one principle may

lessen the capability of another principle. For example, a major transformation in the HHS system has been to increase responsiveness and flexibility through the use of lighter, modular, and forward deployed medical assets. However, these concepts entail a decentralization of operations and thus have potential to compromise the principles of economy, simplicity, and sustainability.

2. Levels of Care

In accordance with the Joint Health Service Support Strategy of Vision 2010 (Force Health Protection, 2003), Levels of Care supersedes the previous terminology of Echelons of Care. As JP 4-02 (2001) details, the medical structure of the Level of Care (LOC) concept consists of "A five-tier phased system of progressively increasing capabilities that begins at the point of injury (POI) and projects rearward to definitive care delivered in the continental United States (CONUS)." The five LOCs are augmented by the patient movement system as depicted in Figure 1.3. Each succeeding LOC possesses the same treatment capabilities as those forward of it and adds a new increment of treatment capability distinguishing it from the previous level. Each level is designed to provide the mobility and capability required to meet the basic healthcare needs of the supported units, yet provide progressive and phased treatment, hospitalization, and evacuation of the sick and injured (NTTP 4-02.2, 2001).

Level of Care I (LI): Care is rendered at the unit and includes self aid and buddy aid care, examination, and emergency lifesaving measures such as maintenance of airway, control of bleeding, prevention and control of shock, and prevention of further injury. This level may include an aid station that has a physician, physician assistant, and/or medical officer (MO). The elements of medical care and management available at this LOC prepare patients for return to duty (RTD) or evacuation to a higher LOC for more definitive care (JP 4-02.2, 1996; NWP 4-02, 1995).

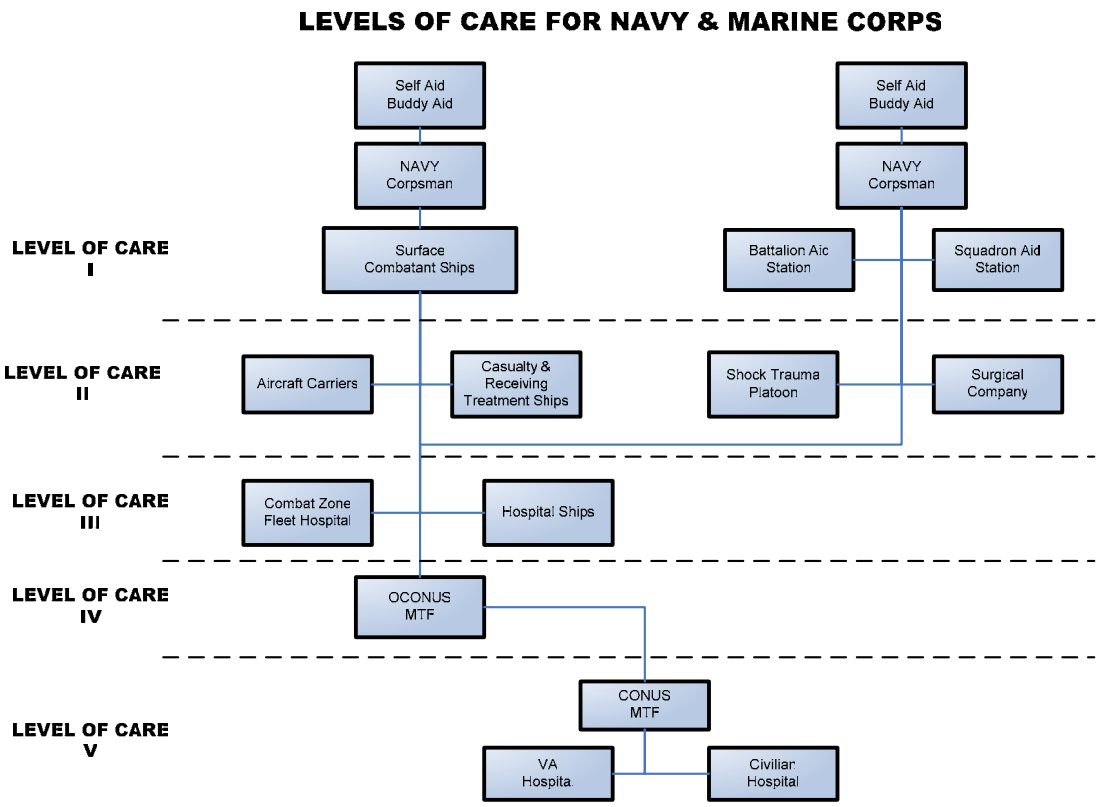

Figure 1.3 Levels of Care (After JP 4-02.2, 1995)

Level of Care II (LII): As a minimum, LII care includes basic resuscitation and stabilization and may include limited surgical capability, basic blood and blood products, basic laboratory, pharmacy, and temporary holding facilities (JP 4-02.2, 1996). In addition to the general medical staff (e.g. nurses, corpsmen, etc), the facilities are also manned by general surgeons and anesthesiologists and/or nurse anesthetists. Other specialties may also be represented. Ancillary support that is provided, particularly laboratory and radiology, is minimal. In the fleet, this level of care is available on the larger ships. For example, surgical capability will be provided by an aircraft carrier in a carrier battle group and by the CRTS (designated ship for treatment and transfer of patients) of an amphibious battle group. In the Fleet Marine Force (FMF), the medical battalion consists of three Surgical Companies and eight Shock Trauma Platoons (STPs) that provide LII care, which includes surgical capability, basic laboratory, pharmacy, radiology, and holding ward facilities. The objective of this phase of treatment is to perform those emergency surgical procedures which constitute resuscitation and, without

which, death or serious loss of limb and/or body function is likely to occur (NWP 4-02, 1995). Surface or air evacuation to a Level III medical treatment facility (MTF) would be utilized for patients who require more comprehensive treatment.

Level of Care III (LIII): Care administered at LIII requires clinical capabilities normally found in an MTF staffed, equipped, and located in a lower level threat environment. LIII care may be the first step toward restoration of functional health, as compared to procedures that stabilize a condition or prolong life. The HSS provided by these facilities, the Hospital Ship (T-AH) and Combat Zone (CBTZ) fleet hospital, will have greater capabilities, particularly in laboratory and radiology support. LIII care may not have the crisis aspects of initial resuscitative care. Therefore, care at this level of treatment can proceed with greater deliberation. Limited specialty surgical capability is available at LIII MTFs. This level of care constitutes the definitive treatment that is needed to return many patients to full duty (JP 4-02, 2001; NWP 4-02, 1995).

Level of Care IV (LIV): Care is provided within a fixed immobile MTF staffed and equipped for definitive care and includes specialized surgical capability (JP 4-02, 2001). In addition to the surgical capability provided in the lower LOC, LIV provides further definitive therapy for patients in the recovery phase who can return to duty within the time period of the theater evacuation policy. Definitive care is normally provided by a Communications Zone (COMMZ) fleet hospital or an OCONUS MTF. This level of care is adapted to the precise condition of the patient, and is normally provided by a fully staffed hospital that delivers the care necessary to complete the patient's recovery (NWP 4-02, 1995).

Level of Care V (LV): Care is convalescent, restorative, and rehabilitative and is normally provided by CONUS-based military, Department of Veterans Affairs, and/or National Disaster Medical System civilian hospitals (JP 4-02, 2001).

The structural makeup of the five LOCs creates a phased system of treatment and evacuation that is commonly termed continuum of care and can be maintained from POI to definitive care without exacerbating a patient's medical condition. A casualty will progressively flow to higher echelons until a facility can provide the required definitive care and allow return to duty, or evacuation to an MTF in CONUS. The continuum of

care as exhibited in Figure 1.4 is designed around the LOCs that manifest as highly mobile elements in the forward areas to more highly sophisticated and capable, but less mobile, elements in the rear. This balance represents a decision point for medical planners as choices must be made to what the appropriate METS structure is and to what extent limited resources should be apportioned to the LOCs. However, the mainstay objective always remains on "Returning as many personnel as possible to active duty and treating and stabilizing those who will not return to duty (NWP 4-02, 1995)."

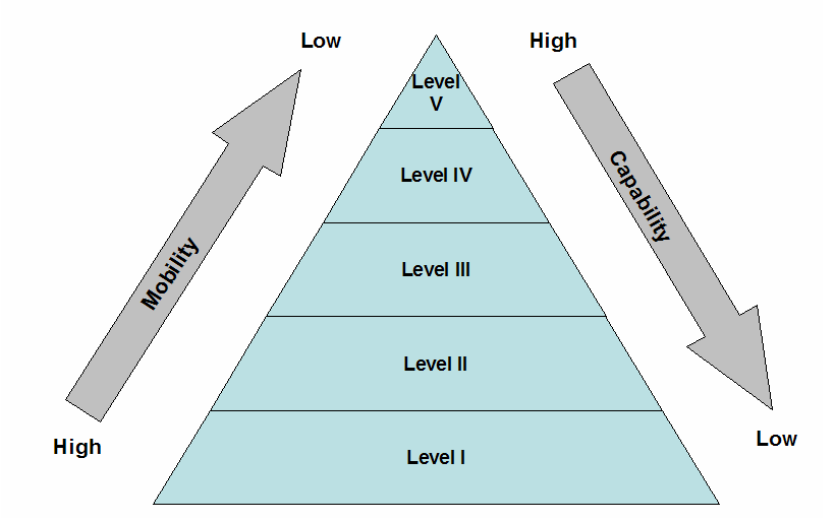

Figure 1.4 Continuum of Care

C. TRIAGE

Doctrine indicates that triage is "The process of utilizing limited assets and time to provide the greatest benefit to the largest number of patients (NTTP 4-02.2, 2001; NWP 4-02, 1995)." Triage is a dynamic and continuous process of sorting and allocating treatment assets to patients according to pre-designated, categorical levels representing the type and acuity of injury. Weighted into this triage categorization are the opinions of medical personnel concerning a patient's chances of stabilization and recovery, as well as resource requirements to save life and limb. Each categorization is done independent of other patients and operates in a memoryless system. In otherwords, the categorization of an incoming patient has no dependence upon any previous arrivals (George, 2005).

Triage is conducted as soon as a patient enters the medical system and is modified throughout the time periods and thru each level of care. This is paramount as the

differentiation of critical from non-critical treatment needs assists in identifying where limited medical resources need to be applied. Additionally, the systematic evolution of triage effectively determines what medical treatment can be delayed, what is needed immediately, and which patients may be kept in a medical queue or be most assisted by medical evacuations.

As stated, the assignment of a triage category is dependent upon multiple variables and is a continuous process. An assessment of clinical needs, operational environment, and treatment availability remain the primary variables utilized in evaluating a patient's triage category. As patients arrive at each MTF, they are assigned a triage category and monitored for any significant change in condition that will automatically dictate a re-evaluation. The first four triage categories exhibited in Table 1.1 and more fully described in Appendix B have been universally adopted for use by both U.S. and NATO forces and are clearly defined in International Standardization Agreements (STANAG 2879, 1986). The fifth category of "Deceased" is commonly added for tracking purposes by United States and some allied forces.

TRIAGE CASUALTY CATEGORIES		
Group	**Type**	**Description**
C_1	Immediate Treatment	The immediate treatment group includes patients requiring emergency life-saving surgery.
C_2	Delayed Treatment	The delayed treatment group includes patients badly in need of time-consuming major surgery, but whose general condition permits delay in surgical treatment without unduly endangering life.
C_3	Minimal Treatment	The minimal treatment group includes patients with relatively minor injuries who can effectively care for themselves or receive care from untrained personnel.
C_4	Expectant	The expectant treatment group comprises patients having serious and often multiple injuries, requiring time consuming and complicated treatment with a low chance of survival.
C_5	Deceased	This group is comprised of the killed in action (KIA) and died of wounds received in action (DWRIA).

Table 1.1 Triage Categories (From NTTP 4-02.2, 2001; NWP 4-02, 1995).

D. PATIENT MOVEMENT SYSTEM

The patient movement system consists of three components: patient evacuation, medical regulating, and en route care. While the patient movement system is a major focus of this research, it is noteworthy that it does not operate independently of the other components necessary for a well complemented patient movement system. Each of these components are outlined further in this chapter, but as a functional unit they maintain an overarching objective to move patients from the point of injury (POI) as efficiently as possible, while maintaining the level of care of each patient and not exacerbating their medical condition. Levels of patient care allow health care providers to make decisions relating to a patient's disposition, timely treatment, and subsequent hospitalization based on the availability of transportation to move the patient to more definitive care. Patient movement therefore contributes to minimizing the effects of wounds, injuries, and disease by making planned patient movement and the five levels of care that comprise the HSS system available to the patient (JP 4-02.2, 1996).

The guiding principle in patient movement is that patients will be moved only as far rearward as the tactical situation dictates or as clinical needs change (NTTP 4-02.2, 2001). During intensive conflict phases or within areas coming under enemy fire, medical evacuation may be imprudent or even impossible until the environment allows safer mobility. Additionally, if a unit is in the midst of a maneuver or conflict, there may be little or no resources available to immediately evacuate a casualty out of the area. The effective movement of patients to additional levels of care is driven by medical necessity of wounds and availability of medical resources while efficient utilization of the patient movement system minimizes both morbidity and mortality rates. Foundationally, METS depends on the following factors:

- Acuity of the casualty;
- Operational condition within AO;
- Availability of medical evacuation assets;
- Treatment capability of medical equipment, supplies, and staff;
- Workload projection compared to treatment capacity.

The movement of patients from one level of treatment to another for more definitive treatment, or between and within levels of treatment, requires in-depth

planning, adequate resourcing, and skillful execution. As Kott (1999) states, "Probably the most challenging aspect in planning and scheduling medical evacuation operations has to do with the dynamics of a domain in which requirements and constraints continuously change over time." Medical planners must be attentive to a litany of factors that can greatly influence the efficiency and effectiveness of patient movement. As described by NTTP 4-02.2 (2001), the most common of which are:

- Tactical Situation
- Availability of transportation
- On-hand patient mix
- Medical specialty capabilities & staffing levels
- Class VIII status, medical equipment status
- Location of HSS facilities, and pending displacement of facilities
- Current bed status of facilities (beds occupied/not occupied)
- Surgical backlog of each facility (patients and hours of surgery)
- Number and location of patients by diagnostic category
- Location of airfields or seaports
- Condition of each patient (Is the patient stabilized enough to withstand travel?)
- Communications capabilities
- Availability of patient movement items (PMI) such as litters, monitors, etc.

1. Patient Evacuation

The objective of a robust evacuation system is to obtain the best possible infrastructure and asset allocation to leverage technology and medical specialists, while reducing risk by providing care further away from the dangers and constraints of the combat zone. Patient evacuation is the timely and efficient transportation of wounded, injured, or ill personnel from the immediate area of operations to HSS facilities and, as required, between HSS facilities. Evacuation begins at the location where the injury or illness takes place and continues as far rearward as the patient's medical condition warrants and/or the military situation dictates. In the lower levels in the continuum of care, patients are moved to the nearest HSS facility whereas in the higher levels, they are regulated to a designated facility (NTTP 4-02.2, 2001).

Similar to the triage process, patients are prioritized for evacuation by a hierarchal categorization that factors in their medical condition and the ability of the evacuation asset to transport each patient. This categorization, as depicted in Table 1.2, determines how quickly a patient is targeted for evacuation within the patient movement system. It is determined at the originating facility and may be upgraded or downgraded at each succeeding level of patient care (JP 4-02.2, 1996). Medical regulators must factor a myriad of variables when assigning an evacuation priority, the most prominent of which is will the patient's condition be exacerbated by conditions and limitations of the AO and the medical evacuation asset. Prior to any evacuation, a patient must be stabilized enough to transit to the next MTF and within the medical capabilities of the receiving MTF.

PATIENT MOVEMENT SYSTEM		
CATEGORY	**DESCRIPTION**	**TIME TO EVAC (USN)**
URGENT (Priority I)	Patients who require emergency, short notice evacuation within a maximum of two hours to save life, limb, or eyesight and to prevent serious complications of the injury, serious illness, or permanent disability.	Within 2 Hours
PRIORITY (Priority II)	Patients who require prompt medical care, within a maximum of four hours, to prevent the medical condition from deteriorating to an URGENT precedence, to prevent unnecessary pain or disability, or who require treatment not available locally.	Within 4 Hours
ROUTINE (Priority III)	Patients who do not require immediate medical attention and whose condition is not expected to deteriorate significantly.	Within 24 Hours
CONVENIENCE (Priority IV)	Patients for whom evacuation by medical vehicle is a matter of medical convenience rather than necessity.	No Limit

Table 1.2 Evacuation Time Periods (After JP 4-02.2, 1996; NTTP 4-02.2, 2001)

Casualties are evacuated through the HSS system until they arrive at a facility having the capabilities required to begin decisive intervention, the time required to perform necessary procedures, and the bed capacity to retain the patient. This MTF or level of care is defined as the site of principal treatment (NWP 4-02, 1995).

2. Theater Evacuation Policy

The theater evacuation policy is set by the Secretary of Defense in coordination with the Joint Chiefs of Staff (JCS) and in agreement with the geographic combatant commander (COCOM) prior to operation plan (OPLAN) execution (JP 4-02.2, 1996). The policy designates the maximum number of days a patient may be held (treatment and recovery) at each level of care in the AO and combat theater. If in the medical officer's (MO) opinion, the casualty cannot return to duty (RTD) within the specified number of days, the casualty should be evacuated as soon as clinically and tactically possible. Traditionally, the evacuation policy is seven (7) days for the combat zone and a combined total of fifteen (15) days for the combat zone and the communications zone.

This policy is flexible and can be adjusted by the COCOM as the tactical situation dictates. As evidence of this it is common that if a stabilized patient who is clearly not going to be able to RTD within the Theater Evacuation Policy will be evacuated out of the immediate combat theater or CONUS for continued treatment, providing that evacuation will not exacerbate the patient's condition (NTTP 4-02.2, 2001)

In constructing an evacuation model, multiple dimensions of objectives, preferences, and constraints need to be balanced. Some primary objectives include:

- Minimizing the queue lengths of casualties awaiting evacuation.
- Number of patients evacuated to appropriate level MTFs is maximized, with a weighted system favoring critical and urgent patients over routine ones.
- Maximizing aircraft vehicle capacity use.
- Minimizing the number of aircraft missions.
- Minimizing flight time and number of stops during each flight.

Theater evacuation policy has significant impact on the requirements for size, mobility, and capabilities of the HSS system. Advocating a shorter or longer evacuation policy has ramifications that must be considered and applied carefully by the COCOM and Joint Forces Surgeon (JFS). As stated within the Navy Tactics, Techniques, and Procedures manual (2001), every patient evacuated without sufficient reason imposes unnecessary burdens on:

- Their unit, which will be understaffed until the patient is returned or replaced.
- The replacement system that must procure, train, and transport a replacement.
- The HSS system that must provide bed space and personnel for each casualty.

A shorter theater evacuation policy will result in fewer beds being required within the area of operations (AO), but the benefits of doing so may be offset by any of the following:

- The cost of realigning more beds out of theater.
- Creating greater demand and dependency on medical evacuation assets.
- Reduce the number of casualties in theater that are able to RTD.
- Cause MTFs to be overwhelmed if mass casualties occur and evacuation assets are unable to offset the casualty inflow.

A longer theater evacuation policy will reduce bed requirements out of the theater and increase the proportion of casualties able to RTD, but it will also create the following issues:

- Shift the beds requirement in-theater and necessitate larger MTFs within the AO.
- Increase the population at risk (PAR) by maintaining more personnel within the combat zone.
- Require greater utilization of medical supplies, logistics, and medical staff within the AO.

3. Medical Regulating

The continuity of care concept within the METS is accomplished through the execution of theater policy by medical regulators. According to JP 4-02.2 (1996), medical regulating in itself "Entails identifying patients requiring medical care beyond that which is available at their present location, locating and assigning a patient to a hospital with appropriate capability, and coordinating the transportation means for movement." This process is vital as it ensures that both the bed capacity and medical capability are present at an MTF in order to maintain or better the health of any casualty.

Patients are not regulated from Level I (Battalion Aid Stations (BASs), Beach Evacuation Stations (BESs) and Shock Trauma Platoons (STPs)) to Level II (Surgical

Company and Casualty Receiving and Treatment Ships (CRTS)), they are evacuated to the nearest medical entity. At this level in the HSS system, only flow-through beds exist which consist of basic cots with no particular design specific to assist in medical care. True hospital beds exist only at Level III and above. STPs and surgical companies holding beds are cots and may normally only hold patients for up to 72 hours only (NTTP 4-02.2, 2001).

4. Enroute Care

A major complexity within the METS system is the locality and sustainment of necessary medical personnel and patient movement items (PMIs). Neither are fixed assets and must accompany patients that are evacuated, thereby reducing the capacity at the sending MTF. While some air evacuations are beginning to have organic medical personnel attached with them, it is still the expectation that the sending MTF supplies the necessary personnel and medical items. This ensures that a continuity of care exists and the patient remains stabilized throughout the entire evacuation. Due to the nature of this interdependence between treatment and evacuation, the capability of MTFs can be quickly depleted if the return of medical personnel and materiel do not match the outflow of casualties requiring enroute care evacuation.

5. Special Considerations

As with any operation, contingencies must be planned for both low probability-high demand and high probability-low demand scenarios. The most common of the former are CBRNE contaminated patients that present, causing major complexities within the treatment and evacuation processes. According to Smith (1995), during the Gulf War of 1991, Naval HSS were told that contamination of patients could be seen in as much as 15% of the casualty population. Doctrinally, contaminated personnel will not routinely be enplaned on aeromedical evacuation aircraft as such an aircraft becomes contaminated as a result and lost from service until decontaminated (JP 4-02.2, 1996). Thus, these patients require special medical attention and logistical support that further taxes the METS capacities.

Of equal concern is the high-probability low-intensity scenario of the treatment and evacuation of enemy prisoners of war (EPWs). Per Geneva Conventions, EPW patients must receive the same quality of care provided to the detaining power's own

troops. Thus, they will compete for the same limited medical resources and evacuation assets as all other patients. Doctrine indicates that "Qualified medical retained personnel (RP) will be used as much as possible in medical and hygiene work needed for the well-being of EPWs (JP 4-02.2, 1996)." However, even though the use of RP staff may alleviate the draw upon medical staff, the EPWs will still reduce limited medical supplies and the addition of RPs will further reduce available evacuation capacity.

Additionally, as occurred in OIF, the protracted post-conflict insurgencies have required many of the mobile medical units to transform into fixed facilities within their area of responsibility (AOR). According to Gawande (2004), this has brought a flood of Iraqi civilians (particularly pediatric patients) seeking care, overwhelming an already resource constrained medical capabilities. Unless NATO or host nation support (HNS) is facilitated, the in-theater MTFs may bare the full brunt of providing these services.

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II. LITERATURE REVIEW

The preservation of the soldier's health should be [the commander's] first and greatest care."

- George Washington[2]

A. MULTIPERIOD/INTER-TEMPORAL NETWORKS

To date, inter-temporal or multi-period models have been almost exclusively utilized within the industrial and financial industries (Sahinidis and Grossmann, 1991). Initial utilization within the health care industry has lent much of the analysis to focus on either patient flow through a network or resource allocation, but none that have encapsulated both processes at once.

The resource allocation process was addressed by van Zon and Kommer (1999) in a deterministic allocation model based upon the inter-temporal assumption that resource allocations within medical systems would most certainly affect those to be taken in the future. As exhibited in Figure 2.1, the network delineates three specific stocks of patients (denoted by the W circles) who are in the beginning of the system at the beginning of a period.

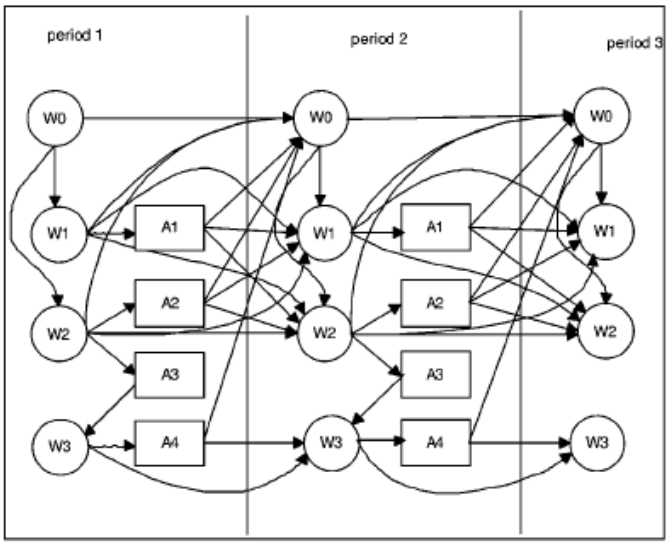

Figure 2.1 Inter-Temporal Model of Patient Flow (From van Zon & Kommer, 1999)

[2] (As cited from Joint Pub 4.02, 2001)

The rectangles represent medical activities while the arcs are the flow of patients thru these activities. Key findings from this model were that minimizing waiting times does not necessarily lead to an increase in welfare and may actually be counterproductive to policy goals. In fact, as shown by others (Tavakoli, Davies, Malek, 1999), in some circumstances, targeting the waiting times may actually lengthen the queue or be counterproductive in the health management of patients (van Zon and Kommer, 1999). The model also emphasized that a quantifiable "shadow-price" could be associated to certain metrics thereby directly indicating the benefits that could be achieved thru different processes. The information produced by the model provides the information necessary for decision makers to associate costs with specific policies that delineate how mismatches between the demand and supply of health-care can be mitigated.

B. EVACUATION

Cook (1977) delineated a medevac problem similar in its linear constraints to many generalized personnel scheduling problems. Basing the model upon a deterministic patient inflow, the research exhibited that the model was useful in maintaining a set of medical service levels while minimizing required staff. However, even with a simplified model, the solution was confounded by quadratic constraints and inability to meet all goals. Thus, while feasible solutions were obtainable, they by their own omission did not necessarily take advantage of any special structuring inherent in the problem.

Kott et al. (1999) presents a model that determine the optimal size and mix of means of transportation that satisfy certain operational requirements. Findings included benefits in continuity by devising a dynamic replanning technique that regenerates plans while the currently executing plan is utilized as a constraint on the solution. Similarly, Sundstrom et al. (1996) devised a linear program (OPTEVAC) that attempted to determine optimal placement and number of evacuation assets within a given theater of operations. Utilizing the Probabilistic Location Set Covering Problem (ReVelle & Hogan, 1989), they were able to exhibit that significant resources of ground and air ambulances could be optimized within a specific theater of operations.

C. PATIENT FLOW AND RESOURCE MODELS

Numerous studies (Harper, 2002; Harrison, 2001; Millard et al., 2004; Riggs, 1978) highlight the inherent fact that demand for medical services often exceeds the supply and thus causes rationing of services. In fact, queues, denial of treatment, or lowered intensity of delivered services should be expected and are critical measures for policy planners to focus on when assessing the operation of their organization. Additionally, these studies assist in creating awareness of the complex and dynamic nature of medical systems and support the necessity for models that reflect the uncertainty, variability, and limitations associated with accommodating actual patient demand.

Lehaney, Kogetsidis, and Clarke (1996) utilized a PC windows-based simulation to model the variable demand emplaced upon hospital clinic resources caused by a range of scenarios. The model while simple, exhibited effectiveness at quantifying the total time in system for patients who flowed along different routes within the clinical process and expressing queue build-ups at specific points.

Application of the Harrison and Millard Flow Model (BOMPS) and Sorenston's multi-phased bed model were utilized by Mackay (2001) to provide Australian health planners relevant information on patient flow, bed blockages, length of stay causations. This was extremely important as other research by Bagust, Place, and Posnett (1999) highlight that bed occupancy in excess of 90% may result in periodic bed crises in an acute care setting.

D. MILITARY MEDICAL SIMULATION AND MODELING

Modeling and Simulation (M&S) has long been used by the Navy in operational planning and has slowly expanded into the modeling of medical planning metrics as well.

1. Medical Analysis Tool

The Medical Analysis Tool (MAT) remains the primary tool with which planners in the J4 shop determine the level and scope of medical support needed for a joint operation. Its mainstay modules consist of a medical requirements estimator (MRE) and a course of action (COA) planner that can be used for both deliberate and crisis-action planning. Specifically, MAT is effective at exhibiting requirements for beds, operating rooms, blood items, and personnel required to complement the projected patient casualty

rates. MAT also identifies bottlenecks within the medical system and reports out a risk assessment based upon the associated HSS system (Marghella, 2003). While remaining an instrumental decision aid in current operational planning for medical services, MAT is still viewed by many providers and planners an "Incomplete tool for providing the fidelity and type of planning data needed to support medical operations (Medical Seabasing, 2004)."

2. Tactical Medical Analysis Tool

The Tactical Medical Analysis Tool (TML+) is a simulation driven model that primarily deals with flow of patients from the point of injury through more definitive care. It has further developed into a tool that can be utilized for operational risk assessment and medical services planning.

TML+ builds upon some of these previous models and further enhances the ability to model a patient flow of casualties within a specific network of treatment facilities from POI to definitive treatment. Other additions include the ability to simulate the treatment times and demands on consumable supplies, equipment, personnel, and transportation assets in the AO (Tropeano, Konoske, et al., 2003). Utilized with additional planning tools, TML+ maintains excellent capabilities in both deliberate and crisis action planning.

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III. METCOM DESIGN & UTILIZATION

"Blood is the price of victory"
- Karl von Clausewitz[3]

A. OBJECTIVES OF THE MODEL

The primary objective of METCOM is that thru the utilization of specific measures of effectiveness (MOEs) design an integrated METS network that will provide quantitative data to decision makers in order to facilitate better functioning and strategic integration of the HSS system into the overall concept of operations. The model centers on the treatment and evacuation capacities in order to highlight the effects that deployed medical infrastructure and policy have on the pre-defined MOEs. Specifically, the model focuses on the integration of Level II and III MTFs within the METS as these LOCs constitute the major medical delivery assets within the forward theater of operations and have significant capability to negate or reduce mortality and morbidity levels of the population at risk. Additionally, of all the LOCs, Levels II and III have the greatest potential and adaptability to change their design, structure, and capabilities to meet evolving operational needs and future strategic initiatives.

The model is targeted to address the following key issues:

1. *For a given operational scenario in a certain theater of operations, what is the optimal METS structure and most efficient mix of evacuation and medical treatment capabilities at each LOC such that specific MOEs are satisfied?*
2. *Given a specific METS structure, what policy is most effective with regards to chosen MOEs?*
3. *How sensitive are the MOEs to the METS structure, applicable theater policies, and casualty flow fluctuations that are predicted to occur over the length of the OPLAN.*

[3] As cited from http://www.jmacsnippets.net/Quotes_Clausewitz.htm, April, 2005

B. STRUCTURE OF THE GENERAL METS NETWORK

The Medical Evacuation and Treatment System (METS) is represented as a multiperiod network that captures the structural and operational dimensions of delivering combat healthcare and executing medical evacuations (MEDEVACs). METCOM allows for the analysis of alternative METS structures and policies and exhibits how such alternatives would affect key measures of effectiveness (MOEs). Figure 3.1 exhibits the generic setup by depicting the structural dimension of METS consisting of levels of care (LOC) along the vertical axis, and time periods along the horizontal axis. Within each block of the time-level network, the operational dimensions consisting of the dual processes of treatment and evacuation are represented.

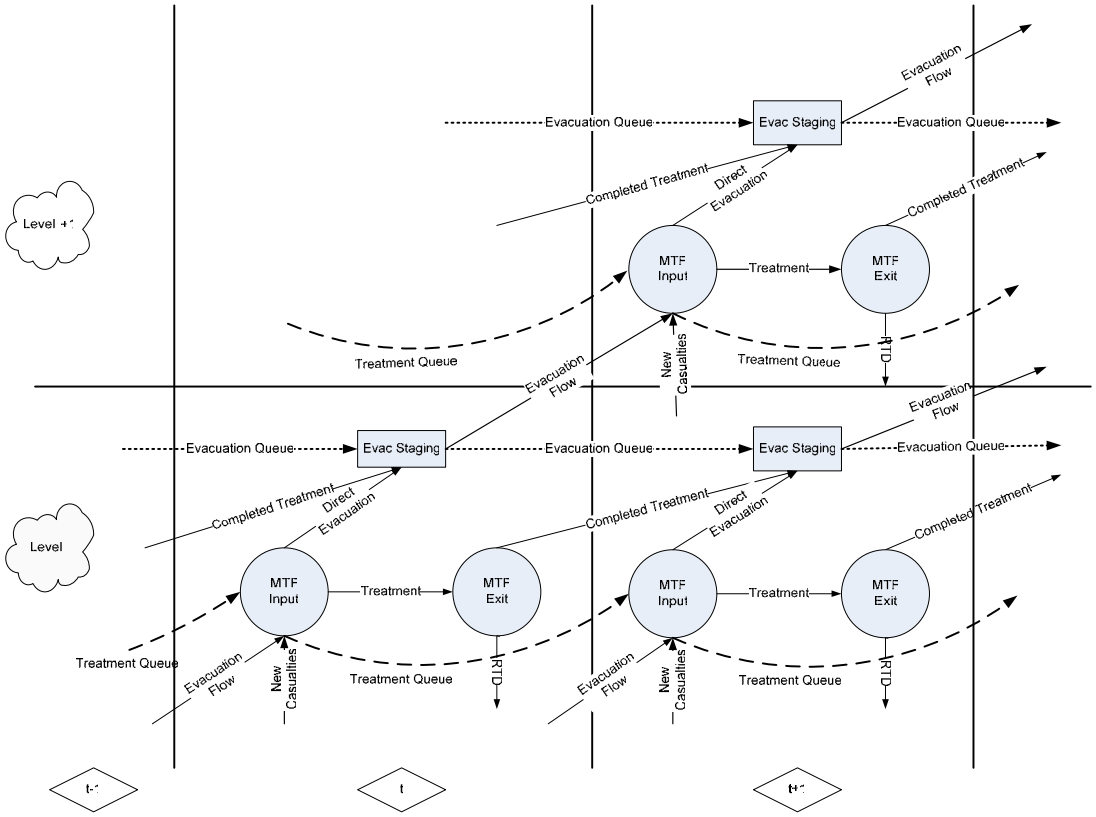

Figure 3.1 METS General Network

Each node in the METS network represents a servicing point for medical treatment or evacuation with associated priorities and constraints. The circular nodes represent the medical treatment facility (MTF) where the treatment process is carried out while the block nodes represent the mobile aeromedical staging facility (MASF) which

conducts the evacuation process. Casualties flow from node to node along the arcs of the network with those in a queue represented by a dashed arc and those in the midst of a treatment or evacuation process represented by a solid arc. As the inflow of casualties arrive at each node the process of treatment or evacuation is governed by a specific priority rule based upon a theater treatment and evacuation policy that is generally directed by the COCOM or JFS. Specific policies will be addressed later in this chapter as they constitute a major driving force on the effectiveness and efficiency of the METS network.

Although Figure 3.1 depicts just two levels of care (i=2), the full network would consist of medical treatment being phased through the structure of up to five LOCs ($i \leq 5$) with basic first aid beginning at Level I and progressing towards definitive care provided at a Level V CONUS medical treatment facility. The time period of the scenario is exhibited as occurring over three time periods (S=3), but practical application of METCOM allows for operational length to be set per the medical planners' and regulators' choosing, or simply the time horizon given in the operation plan (OPLAN).

Additionally, the defined length of the time periods remains flexible and is user selected in order to allow for testing time period effects on the METS network, compare alternative policies, or simply fit most appropriately with the time-phased force deployment data (TPFDD). The variability in time resolution may result in significant topology adjustments in the METS network. For example, the MOEs may exhibit stark differences in the induced graphs if the time step is changed (e.g. 1 hour to 3 hours) while holding the length of treatment constant at three hours. This feature is particularly useful when wishing to ascertain different time-dependent casualty flow rate affects upon key MOEs. Such scenarios, as a spike in injuries induced from a mass casualty incident(s), can be modeled by shortening the time periods which causes an increase in arrival rate and necessitates greater utilization of the METS network. On the opposite spectrum, if long durations of minimal patient flows are warranted as seen in many low-intensity or post-conflict scenarios, the time periods can be lengthened, causing arrival rates to decrease.

C. GENERAL METS NETWORK PROCESSES

For simplicity we assume that the METS is modeled such that any single process (treatment or evacuation) takes exactly one time period to complete. As discussed above, different time scales induce different graph topologies. Since both processes cannot occur in the same time period for the same casualty, planners must prioritize whether a casualty will be evacuated or treated in each period. This necessitates a flexible yet resource constrained policy that outlines the appropriate prioritization for treatment and evacuation timelines for casualties and significantly impacts the structural requirements of the METS. Further, this policy represents the theater treatment and evacuation policy that will be executed and maintained by the COCOM. The basic flows of the General METS network are defined next. We define three auxiliary variables: *MTF Input, EvacStaging and MTF Exit* that represent a population of casualties at a given time and place within the METS.

System Arrivals:

In general, casualties arrive at a MTF either from the battlefield or from a lower LOC. At LOC I, new arrivals consist of the combat casualties incurred in the current time period. This flow is supplemented with casualties that have been delayed in the treatment queue from the previous period. As this is the lowest LOC, casualties cannot be received via any type of evacuation flow occurring from lower level MTFs.

At LOC II thru LOC V, new arrivals consist of casualties received via the evacuation flow from a lower level of care in the previous time period. Just as at LOC I, this is supplemented with casualties that have been delayed in the treatment queue of that MTF from the previous period. Due to the tiered structure of the METS, new casualties in the combat zone are received only at LOC I, thus at all higher LOCs no casualties are directly received from the combat field. The balance equations for the inflow of casualties are as follows:

LOC I Specific:

$$\underbrace{MTF\ \ Input}_{\substack{\text{Casualties}\\ \text{entering the}\\ \text{MTF.}}}(t) = \underbrace{TreatmentQueue(t-1)}_{\substack{\text{Delayed treatment flow from}\\ \text{the previous time period.}}} + \underbrace{NewCasualties(t)}_{\text{New combat casualties.}} \tag{3.1}$$

LOC II thru LOC V Specific:

$$\underbrace{MTF\ \ Input}_{\substack{\text{Casualties}\\ \text{entering the}\\ \text{MTF.}}}(t) = \underbrace{TreatmentQueue(t-1)}_{\substack{\text{Delayed treatment flow from}\\ \text{the previous time period.}}} + \underbrace{EvacuationFlow(t-1)}_{\substack{\text{Those evacuated from a lower}\\ \text{LOC from the previous time period.}}} \tag{3.2}$$

<u>Treatment:</u>

All casualties can be treated up to the extent of the medical capacity of the MTF, which is driven by availability of supplies, equipment, personnel, blood products, beds, combat environment, and a host of other internal and external factors. If policy allows or requires the MTF to accept a greater number of casualties than its treatment capacity, then casualties above the capacity will be delayed in a medical queue that flows into the next time period as represented by the horizontal dotted arc *Treatment Queue*. The balance equation for medical treatment and the associated treatment queue are derived from the following:

$$Treatment(t) = MTF\ \ Input(t) - DirectEvacuation(t) - TreatmentQueue(t) \tag{3.3}$$

<u>Evacuation:</u>

Similarly, the evacuation flow is also subject to maximum capacity constraints that are determined by the availability of evacuation assets' (dedicated, designated, lifts of opportunity), applicable litter and seat configuration, requirement for patient movement items (PMIs), organic medical personnel and equipment, and feasible evacuation range. Casualties that satisfies the maximum evacuation capacity constraints will be evacuated to the next higher LOC in the next time period as represented by the arc from *Evac Staging(t)* $\rightarrow$ *MTF Input(t+1)*. However, patients above the capacity will be delayed in a staging queue as represented by the horizontal dotted arc *Evacuation Queue* flowing from *Evac Staging(t)* $\rightarrow$ *Evac Staging(t+1)*. The balance equation of the evacuation flow and the associated queue are derived from the following:

$$\underbrace{EvacStaging(t)}_{\substack{\text{The evacuation}\\ \text{staging area.}}} = \underbrace{DirectEvacuation(t)}_{\substack{\text{Casualties being evacuated}\\ \text{with no treatment in}\\ \text{time period t.}}} + \underbrace{EvacuationQueue(t-1)}_{\substack{\text{Casualties who were delayed}\\ \text{in the evac queue from the}\\ \text{previous time period.}}} + \underbrace{CompletedTreatment(t-1)}_{\substack{\text{Casualties who completed}\\ \text{treatment in the previous}\\ \text{time period and were sent}\\ \text{for evacuation.}}} \tag{3.4}$$

System Departures/Exit:

Casualties that complete one time period of treatment are considered completed with treatment (CompTre) at that LOC and are either returned to duty (RTD) or require more definitive care and are sent to the staging area in preparation for evacuation to the next higher LOC in the next time period. This latter process is represented in the *Completed Treatment* arc that flows from the *MTF Exit(t)* $\rightarrow$ *Evac Staging(t+1)*.

$$\underbrace{MTF\ \ Exit(t)}_{\substack{\text{Casualties completing}\\ \text{one time period of}\\ \text{treatment.}}} = \underbrace{MTF\ \ Input(t)}_{\substack{\text{Casualties treated}\\ \text{in period t.}}} - \underbrace{DirectEvacuation(t)}_{\substack{\text{Casualties sent directly}\\ \text{to evacuation staging}}} - \underbrace{TreatmentQueue(t)}_{\substack{\text{Delayed treatment from}\\ \text{the current time period}}} \quad (3.5)$$

Casualties physically exit the network via the treatment process that either provides definitive care and is able to return the casualty to duty (RTD) or is unable to save the casualty's life which constitutes a Died of Wounds (DOW) end state. It should also be noted that the highest LOC V, which is not modeled in our design, is an absorbing state as patients will not RTD or evacuate from this MTF to any additional nodes. The RTD proportion is based upon the propensity that a number of casualties who complete a period of treatment will have received satisfactory treatment to be redeployed to combat operations. This is accomplished through multiplying the number of completed treatments in a time period by a parameter (α) that specifies what proportion of casualties who complete treatment at a specific LOC will RTD. Casualties that are fully treated and ready to return to duty exit the network via the RTD arc emanating from the *MTF Exit* node.

$$RTD(t) = \alpha MTF\ \ Exit(t) \quad (3.6)$$

Although it is acknowledged that the issue of DOW is significant morally, emotionally and politically, it was explicitly removed from the METS model for two primary reasons. First, incorporating a zero DOW policy leads to a greater number of casualties to remain in the system, thereby creating greater utilization of the METS. This allows for the METS network to be maximally stressed and exhibit the system's functioning capacity when the worst case number of casualties are received and

maintained in the system. Second, the DOW casualty population is easily encompassed into other categorical casualty populations that will be discussed later in this chapter.

D. METS THEATRE POLICY

As previously discussed, theater METS policy must be aligned with operational plans and objectives while weighing the resource and human costs associated with a potential course of action (COA). Specifically, the COCOM must decide whether METS policy will be geared more heavily towards evacuation, medical treatment, or some mix between the two. Each COA may produce significantly different casualty flows and thereby produce competing options for decision makers to select during specific combat operations. METCOM is designed to exhibit how different policies affect different casualty flows and may result in different outcomes of the MOEs. Thus, METCOM can assist the decision maker in choosing a policy that best meets and sustains the appropriate level of casualty care warranted by the MOEs.

Figure 3.2 below exhibits the architecture of a more detailed model in which variations of the METS policy can be evaluated. Similarly to the general network, the METS policy network is structured as five LOCs ($i \leq 5$) with basic first aid beginning at LOC I and progressing towards definitive care provided at a LOC V CONUS medical treatment facility (MTF). The medical treatment process has 3 nodes *Input*, *Intermed*, and *Exit* that represent the phased treatment processes (GenTre & SpecTre) within the MTF. Once again, GenTre represents the basic medical services such as physical examination, vital-checks, and general bed allocation that every casualty receives while SpecTre represents the specialty medical care such as intensive care, surgery, or diagnostic testing done only on patients that warrant such specific care. The evacuation process has 1 node labeled *Evac Stage* that represents the mobile aeromedical staging facility (MASF) where casualties await assignment of seats on the medical evacuation asset. For this specific model this staging area is considered removed from the configured bed capacity of the MTF. Casualties flow along the arcs from node to node and are identified as being in queue by a dashed arc or actively in a process by a solid arc.

The arcs in the more detailed METS network are as follows:

Where i = the level of care

c = triage category

w = evacuation priority

- $\left(T1^i_{cw}, T2^i_{cw}, T1Q^i_{cw}, T2Q^i_{cw}\right)$ represent the flow of casualties within the medical treatment process either receiving or waiting to receive a particular phase of care.
  - *T1* is the flow of casualties receiving GenTre.
  - *T2* is the flow of casualties receiving SpecTre.
  - *T1Q* is the flow of casualties in a medical queue who have not received any care.
  - *T2Q* is the flow of casualties in a medical queue who have received GenTre but not SpecTre.
- $\left(H1^i_{cw}, H2^i_{cw}, H3^i_{cw}, HQ^i_{cw}\right)$ represent the flow of casualties within the evacuation staging process at the MASF or attempting to proceed to the next higher LOC.
  - *H1* is the flow of casualties to the MASF with NonTre.
  - *H2* is the flow of casualties to the MASF who have received GenTre only.
  - *H3* is the flow of casualties to the MASF who have received CompTre.
  - *H*Q is the flow of casualties with the evacuation queue at the MASF.
- $\left(E^i_{cw}\right)$ represents the flow of casualties that have cleared the (MASF) and are processing to the next higher LOC.

Each of these arcs is discussed more at length in the following sections. The resulting METS descriptive policy network has been structurally modified from the general network to add more realism to the delivery of treatment as well as differentiate casualty flow by type and severity of injury. Some of the important structural implications of the METS network include:

- Having the *T2Q* casualties flow to the *Input* node rather than *Intermed* node allows for the priority policy to be implemented each time period in a more efficient manner. In that, casualties flowing on the *T2Q* arc have the ability to be evacuated in the very next time period from the *Input* node vice waiting an additional time period if the arc were to flow into the *Intermed* node. Also, if remained in treatment, they consume GenTre resources (capacity).

- Having the *H2* and *H3* casualties flow to the *Evac Stage* node in the next time period versus the current time period represents that the two competing

processes of treatment and evacuation cannot be carried out in the same period.

These changes are discussed more at length below and include the following modifications; delineation of medical treatment into a two-phased process, incorporation of multiple queues within an MTF, and multiple casualty flow through the use of Triage Categories (TriCats) and Evacuation Priorities (EvaPris).

Phased Treatment:

The two-phase treatment process is described by 3 nodes labeled *Input*, *Intermed*, and *Exit*. This divisional treatment setup is representative of the fact that all casualties receive general treatment for their wounds and consume general medical resources such as beds, while only some require additional specialty treatment such as surgery or intensive care. While both treatment types may be accomplished in the same time period, as previously stated, any treatment activity that is done on a casualty will constitute significant usage of the time period and will functionally negate evacuation until the next time period.

This model assumption is exhibited in the three unique flows of casualties within the evacuation process. *H2* and *H3* represent casualties that have received general treatment (GenTre) only and complete treatment (CompTre) respectively. That is, the flow on *H2* represents casualties that did not receive specialty treatment (SpecTre) and are being evacuated while the *H3* edge represents those casualties who did receive SpecTre and are being evacuated. However, as both *H2* and *H3* have received at least some treatment during this time period, they may not be fully evacuated beyond the MASF until the next time period. *H1* represents new casualties or casualties who have arrived from lower LOCs who receive no treatment at the current LOC. They either warrant evacuation priority over medical treatment or they could not be accommodated by the medical treatment process (they were above GenTre capacity) and are sent directly to the evacuation staging area in the current time period.

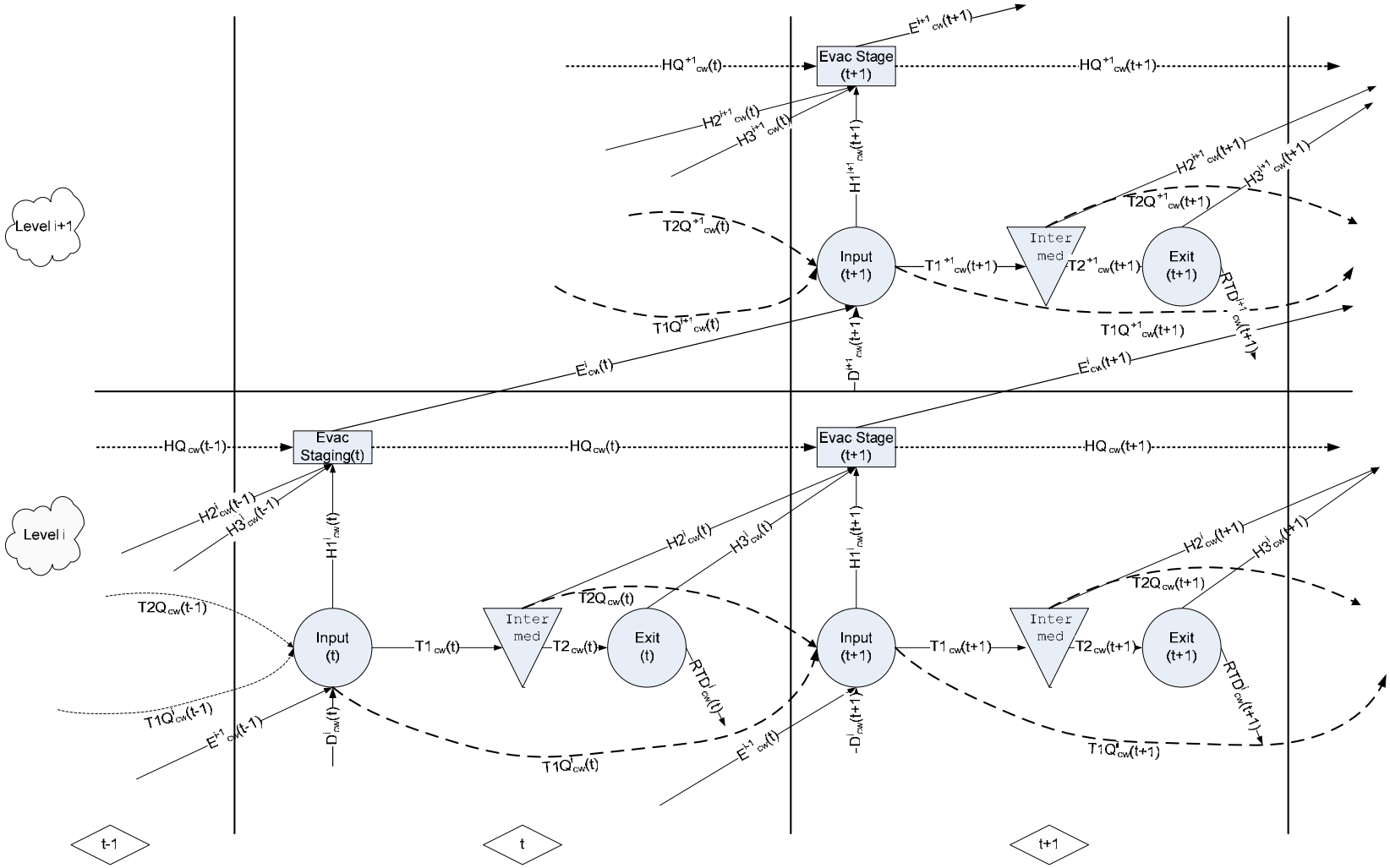

Figure 3.2 METS Descriptive Model

Casualty Flows:

The arrival of new casualties to the system in the expanded METS network images the process of the general network. However, as the treatment of casualties is now represented in two phases, general and specialty, there exists an additional set of queues that maintain casualties in a delayed medical status at the MTF. These and the other arrivals to the system are represented in the following flows:

- New combat casualties of type cw $\left(d_{cw}^{1}\right)$ that arrive to the system (occurs only at LOC I).
- Evacuated casualties of type cw $\left(E_{cw}^{i}\right)$ from LOC (i-1) that arrive to LOC i (occurs for i= II thru V).
- Treatment queue 1 $\left(T1Q_{cw}^{i}\right)$ into the *Input* node of the MTF represents the flow of patients who have received no prior treatment (NonTre) at this level of care and are being delayed in the medical treatment queue.
- Treatment queue 2 $\left(T2Q_{cw}^{i}\right)$ into the *Input* node of the MTF represents the flow of patients who received prior General Treatment (GenTre) but not Specialty Treatment (SpecTre) and are being delayed in the medical queue.

Multicommodity Flow:

The acuity level of casualties presenting for treatment in each LOC is driven by the patient TriCats that consists of four triage categories (c=1,…,4). These TriCats, as explicitly defined in Chapter I, are associated with acuity of injury and are one basis for decision makers to utilize in determining policy on priority for medical treatment. The default policy of METCOM represents the typical policy which places priority on saving life and limb over treating all patients equally. Thus, *immediate* casualties have the highest priority followed by *urgent, minimal,* and *expectant* in successive prioritization order. Change to this policy will implicitly change requirements within the METS and may have a host of effects upon the MOEs. This is a key flexibility of METCOM as it can adaptively change to warranted prioritization policies and reflect outcome measures that assist decision makers in selecting policies that contain acceptable outcomes and risk.

Much like the medical process utilizes TriCats for identifying treatment prioritization, the evacuation process utilizes Evacuation Priorities (EvaPris) of casualties

to assign precedence for MEDEVAC. These EvaPris, also explicitly defined in Chapter I, are associated with the TriCats and the current evacuation propensity for each casualty type. They are categorized into a four tier (w=1,…,4) hierarchy consisting of: *urgent*, *priority*, *routine*, and *convenience*. Although very similar to the triage categorizations, there is not a simple 1:1 conversion from TriCat to EvaPri as many factors associated with assigning a TriCat in a stable, immobile medical unit are different than factors influencing an evacuation capability. For example, medical regulators must consider a litany of internal and environmental factors such as whether there's appropriate medical equipment, personnel, structural setup of the evacuation asset, PMI's, and time to conduct an evacuation. Additionally, some acute medical conditions may not allow for evacuation due to a casualty's mobility constraints, air pressure or altitude constraints for both patient and medical equipment, or even motion of the evacuation asset exacerbating the medical condition.

Again, the default policy of METCOM represents the typical policy which places priority on saving life and limb over treating all patients equally. Thus, *urgent* casualties have the highest priority followed by *priority*, *routine*, and *convenience* in diminishing prioritization order. METCOM also allows for sub-policies that change evacuation priorities, which again assists in comparative analysis of key MOEs between alternative policies.

The actual assignment of TriCat and EvaPri is accomplished through the following process as explained below:

- Planners input the overall casualties expected. This is generally based upon historical data, input from the military service communities, and COCOM on the intensity and risk associated with the expected OPLAN.
- A probability matrix $\Pi(t)$ as exhibited in Table 3.1 for a certain time period is utilized to assign a specific TriCat and EvaPri indices to each casualty of the input population. Each (c,w) entry in this matrix is the probability that a casualty will be a specific TriCat-EvaPri indexed casualty. This probability matrix is based upon historical data, type and duration of the planned operation, and a multitude of other exogenous factors.

	w_1	w_2	w_3	w_4
c_1	0.10	0.10	0.0	0.0
c_2	0.10	0.10	0.10	0.05
c_3	0.0	0.0	0.10	0.05
c_4	0.05	0.05	0.10	0.10

Table 3.1 TriCat (c) & EvaPri (w) Probability Matrix

As represented by Equation 3.1 the overall casualties and probability matrix generate $d_{cw}(t)$, which explicitly enumerates the number of new combat casualties of type *(c,w)* at time period *t.* This is represented by a 4 x 4 matrix consisting of TriCat (c=1,…,4) and EvaPri (w=1,…,4) indexed casualties.

$$d_{cw}(t) = (Total\#Casualties(t)) \times \Pi_{cw}(t) \tag{3.7}$$

where $\Pi_{cw}(t)$ is the *cw* entry of $\Pi(t)$

An essential property, which is a result of incorporating TriCats and EvaPris within the METS, is that the resulting network is multi-commodity. In fact, every arc contains sixteen (c=4 and w=4) categories of unique casualty categories whose flow is subject to influence by the prioritizations stated in the standing METS policy and sub-policies. Thus, medical planners can differentiate how alternative policies affect individual casualty categories and will further assist in determining whether the respective level of efficiency and effectiveness created in the METS meets determined MOEs.

1. Descriptive Network Formulation

The formal representation of the descriptive model associated with Figure 3.2 is shown below:

Indices

t - Time period	where t = 1…T
i - Medical level of care (LOC)	where i = 1,…,5
c - Triage category of casualty (TriCat)	where c = 1,…,4
w - Evacuation priority category (EvaPri)	where w = 1,…,4

Given Data

S Number of time periods of the operation.

$d_{cw}(t)$ Number of new combat casualties of class (*c,w)* at time period *t.*

$\alpha^{i}_{cw}(t)$ Proportion of class (*c,w)* casualties at level of care *i* that have received complete treatment and are returned to duty in time period *t.*

$P_{cw}(t)$ The amount of general evacuation resources needed by a casualty of class (*c,w*).

Π_{cw} Probability that a given new casualty is of class (*c,w*)

Decision Variables

$TreCapG^{i}(t)$ General treatment capacity at level of care *i* in period *t.*

$TreCapS^{i}_{c}(t)$ Specialty treatment capacity of type *c* casualty at level of care *i* in time period *t.*

$EvaCapG^{i}(t)$ General evacuation capacity at level of care *i* in period *t.*

$EvaCapS^{i}_{w}(t)$ Evacuation capacity of type *w* priority at level of care *i* in time period *t.*

Computational Variables:

$T1^{i}_{cw}(t)$ Number of casualties of class (*c,w)* at level of care *i* that are receiving General Treatment (GenTre) in bed at the MTF during time period *t*.

$T2^{i}_{cw}(t)$ Number of casualties of class (*c,w)* at level of care *i* that are receiving Specialty Treatment of type *c* (SpecTre_c) in bed at the MTF during time period *t*.

$T1Q^{i}_{cw}(t)$ Number of casualties of class (*c,w)* at current level of care *i* having received no treatment and delayed in a queue during time period *t*. This queue is labeled Non-Treatment (NonTre) queue.

$T2Q^{i}_{cw}(t)$ Number of casualties of class (*c,w)* at current level of care *i* having received general treatment in bed and then delayed in a queue for specialty treatment during time period *t*. This queue is labeled GenTre queue.

$H1^{i}_{cw}(t)$ Number of casualties of class (*c,w)* at current level of care *i* having received no treatment at that level and sent directly to evacuation staging in time period *t*.

$H2^{i}_{cw}(t)$ Number of casualties of class (*c,w)* at current level of care *i* having received GenTre in bed and sent to evacuation staging in time period *t*+1 before receiving SpecTre_c.

$H3^{i}_{cw}(t)$ Number of casualties of class (c,w) at current level of care *i* having received complete treatment (CompTre) during time period *t* and are sent to evacuation staging in time period *t*+1.

$HQ^{i}_{cw}(t)$ Number of patients of class (c,*w)* at the current level of care *i* during period *t* being delayed in an evacuation queue.

$E^{i}_{cw}(t)$ Number of patients of class (c,*w)* at the current level of care *i* during time period *t* being evacuated to level of care *i* + 1.

$RTD^{i}_{cw}(t)$ Number of casualties of class *(c,w)* at current level of care *i* who are Returned to Duty during time period *t*.

Balance of Flow

METCOM utilizes four specific auxiliary variables that assist in encapsulating pools of casualty flows during each time period. Specifically the medical treatment process incorporates the three nodes of *Input*, *Intermed*, and *Exit* that represent the following:

Input: The pool of casualties that are arriving via new casualties to the system, delayed in medical hold from the previous time period, or from an evacuation asset from a lower echelon. This pool represents the population of casualties for that specific LOC and time period that must be prioritized for either treatment or evacuation given the capacity constraints.

LOC I Specific:

$$\underbrace{Input^{i}_{cw}(t)}_{\substack{\text{Inflow of}\\ \text{casualties}\\ \text{at MTF}}} = \underbrace{T1Q^{i}_{cw}(t-1)}_{\substack{\text{NonTre queue}\\ \text{from previous}\\ \text{period}}} + \underbrace{T2Q^{i}_{cw}(t-1)}_{\substack{\text{GenTre queue}\\ \text{from previous period.}}} + \underbrace{d_{cw}(t)}_{\substack{\text{Newly arriving}\\ \text{casualties to}\\ \text{the METS}}} \tag{3.8}$$

LOC II thru LOC V Specific:

$$\underbrace{Input^{i}_{cw}(t)}_{\substack{\text{Inflow of}\\ \text{casualties}\\ \text{at MTF}}} = \underbrace{T1Q^{i}_{cw}(t-1)}_{\substack{\text{NonTre queue}\\ \text{from previous}\\ \text{period}}} + \underbrace{T2Q^{i}_{cw}(t-1)}_{\substack{\text{GenTre queue}\\ \text{from previous period.}}} + \underbrace{E^{i-1}_{cw}(t-1)}_{\substack{\text{Evacuated casualties}\\ \text{from level i-1 in}\\ \text{previous period.}}} \;) \tag{3.9}$$

Intermed: The pool of casualties that have been prioritized for medical treatment at the LOC and have thus far received GenTre only. They are again awaiting prioritization for further SpecTre or evacuation per the capacity constraints.

$$\underbrace{Intermed^{i}_{cw}(t)}_{\substack{\text{Number of casualites}\\ \text{who've completed GenTre.}}} = \underbrace{T1^{i}_{cw}(t)}_{\substack{\text{GenTre}\\ \text{casualties.}}} \qquad \begin{array}{l} i = 1,\ldots,5 \\ c = 1,\ldots,4 \end{array} \tag{3.10}$$

Exit: The pool of casualties that have completed both general and specialty treatment (CompTre) and are determined to be either ready to RTD or must be evacuated

to the next higher LOC. Evacuating to higher LOCs represents the presumption that the casualty requires more definitive treatment at a higher LOC and is not ready for RTD status.

$$\underbrace{Exit^{i}_{cw}(t)}_{\substack{\text{Completed}\\ \text{treatment node.}}} = \underbrace{T2^{i}_{cw}(t)}_{\substack{\text{SpecTre}\\ \text{casualties}}} \qquad \begin{array}{l} i = 1,\ldots,5 \\ c = 1,\ldots,4 \end{array} \tag{3.11}$$

<u>Evacuation:</u> The evacuation process contains one node, *EvacStage*, which constitutes a pool of casualties located at a MASF that range from those with no prior treatment to those with completed treatment at lower LOCs. The casualties within this node are then comparatively prioritized for evacuation and are sent to the next higher LOC if they are below the capacity constraint of the evacuation asset(s). If this pool of casualties is above the capacity of the evacuation asset, they will be delayed in an evacuation queue.

$$\underbrace{EvacStage^{i}_{cw}(t)}_{\substack{\text{Medical Evac}\\ \text{MASF}}} = \underbrace{HQ^{i}_{cw}(t-1)}_{\text{MASF Queue}} + \underbrace{H1^{i}_{cw}(t)}_{\substack{\text{NonTre}\\ \text{Casualties}}} + \underbrace{H2^{i}_{cw}(t-1)}_{\substack{\text{GenTre}\\ \text{Casualties}}} + \underbrace{H3^{i}_{cw}(t-1)}_{\substack{\text{CompTre}\\ \text{Casualties}}} \tag{3.12}$$

The remaining computations for the multi-commodity arc flows are explicitly enumerated in Appendix B.

2. Selected Priority Flow Policies

As previously discussed, the organizational structure and designation of appropriate processes is only part of ensuring the efficient and effective operation of the METS. Functionally, it is driven by the policies and procedures that dictate the prioritizing of casualties and METS assets towards medical treatment, evacuation, or some mixture of the two. It is paramount to include prioritization policies within the network flow that will represent the COCOM and JFS desires on a medical treatment or evacuation oriented emphasis of the METS policy and structure. Thus in terms of the model, priority of casualty flow is divided into two types of Primary Priority Policies (PPPs): Treatment first, or Evacuation first. Each of these policies in themselves can have multiple sub-policies that dictate how competition for medical or evacuation capacities is conducted per specific casualty category. METCOM addresses these two PPPs, along with two sub-policies that are further explained below.

Primary Priority Policies (PPPs):

A Treatment Priority Policy (TPP) advocates that the first process attempted at any given time period is to provide medical treatment to all casualties. Only if casualties are above treatment capacities or have completed a full period of treatment will they be attempted to be evacuated. If evacuation capacity is constraining as well, then all casualties who've not completed treatment are delayed in the treatment queue rather than the evacuation queue. However, casualties with CompTre and above evacuation capacity (EvaCapG or EvaCapS) will by default policy be placed in the evacuation queue.

The reciprocal of this is the Evacuation Priority Policy (EPP), which attempts as the first process at any given time period to evacuate all casualties. If casualties are above the general evacuation capacity ($EvaCapG^i$) or the specialty evacuation capacity ($EvaCapS^i_w$), they will then be attempted to be treated. Again, if above the treatment capacity as well, casualties will be delayed in the treatment queue rather than the evacuation queue.

Priority Sub-Policies (PSPs):

Each of the primary policies may also maintain multiple priority sub-policies (PSPs) that direct how capacities are competed for amongst TriCat or EvaPri categories. For example, casualties on the evacuation staging arcs $H1^i_{cw}(t+1), H2^i_{cw}(t), H3^i_{cw}(t)$, $HQ^i_{cw}(t)$ all compete for prioritization of the limited evacuation capacity $EvaCapG^i(t+1)$ and then compete a second time for the casualty specific evacuation capacity $EvaCapS^i_w(t+1)$. Deciding how priorities will be allocated can have significant effect on the flow of casualties through the METS.

The first PSP addressed in METCOM consists of advocating for continuity of care and is deemed a GenTre Priority Sub-Policy (GPSP). Specifically it directs that all casualties who have received general treatment (GenTre) and are being evacuated, as represented by the arc $H2^i_{cw}(t)$, will have complete priority for the evacuation capacity (EvaCapG & $EvaCapS_w$) over all others at that LOC. The GenTre flow will reduce the general evacuation capacity in time period (t+1) by however many casualties are sent to the staging area, leaving any remaining capacity for the next highest prioritization,

NonTre $(H1^i_{cw}(t+1))$ casualties in the next time period. Thus, casualties who have received GenTre only are more likely than NonTre or CompTre casualties to move to the next LOC and continue their medical treatment.

Those already in the evacuation queue $(HQ^i_{cw}(t-1))$ will have the next prioritization followed by the CompTre $(H3^i_{cw}(t))$ flow. This prioritization also allows for control over who is placed in the evacuation queue. Specifically, *H1* and *H2* casualty flows are not sent for evacuation unless they are guaranteed allowable capacity exists for their general needs (P_{cw}) and specialty evacuation priority (w) needs. As stated previously, the CompTre flow *H3* is by default sent to the evacuation staging area in order to free up medical bed space at the MTF whether or not evacuation capacity still exists at the staging facility. Thus, if the general or special evacuation capacity is inadequate for any CompTre casualty, they will be forced into the evacuation queue where they will remain until capacity does become available.

The second sub-policy addressed is the Balanced Priority Sub-Policy (BPSP) which considers the same casualty flows as before, but prioritizes $(H2^i_{cw}(t), H1^i_{cw}(t+1))$ purely by EvaPri. Here, higher priority EvaPris from both flows have evacuation precedence over all lower EvaPris. It is still up to decision makers to direct how equivalent EvaPris from the casualty flows will compete against each other. The current METCOM default is to give priority to GenTre casualties when comparing an identical EvaPri to the NonTre casualty flow. Again, the evacuation queue (*HQ*) and CompTre (*H3*) are given third and fourth priority for capacity respectively.

Specifically, in any treatment oriented policy prioritization within a certain TriCat is according to EvaPri, and in any Evacuation oriented policy the prioritization within a certain EvaPri is according to TriCat. However, for both policies, the population of casualties who have completed treatment at the LOC $(H3^i_{cw}(t))$ will not have any priority for the evacuation staging capacity represented by $EvaCapG^i(t+1)$. This is characteristic of the standard medical policy that once treatment has been completed, a casualty will be removed from the medical treatment bed and repositioned in an evacuation staging bed, thereby allowing for greater treatment capacities of new

casualties at the MTF. Once at the evacuation staging area, this population of casualties will compete with all the other casualty flows for actual evacuation space $(EvaCapS_w^i(t))$ aboard the evacuation asset transiting to the next higher LOC.

E. TPP-GPSP EXAMPLE

To better exhibit how these policies actually affect casualty flow, the computational equations are enumerated below and further discussion highlights the ramifications when the TPP and GPSP are emplaced in the METCOM network.

Determining the Flow of Casualties in GenTre

The flow of $T1_{cw}$ casualties is determined by the minimal value of:

- Those at the MTF awaiting GenTre.
- The remaining general treatment capacity after all casualties with more acute TriCat have been deducted.

$$\underbrace{T1_{cw}^i(t)}_{\text{GenTre casualties}} = \underbrace{Min\left\{TreCapG^i(t) - \sum_{j=1}^{c-1}\sum_{k=1}^{4} T1_{jk}^i(t) - \sum_{k=1}^{w-1} T1_{ck}^i(t), Input_{cw}^i(t)\right\}}_{\substack{\text{Minimum of either GenTre capacity minus sum of all} \\ \text{higher priority triage casualties present} \\ \text{OR} \\ \text{The total number of casualties present at that specific TriCat}}} \quad \forall i,c,w \quad (3.13)$$

Determining the Flow of Casualties in SpecTrec

The flow of $T2_{cw}$ casualties is determined by the minimal value of:

- Those who have received GenTre and are awaiting SpecTre
- The remaining specialty treatment capacity after all casualties with more acute TriCat have been deducted.

$$\underbrace{T2_{cw}^i(t)}_{\text{Casualties receiving SpecTre}} = \underbrace{Min\left\{TreCapS_c^i(t) - \sum_{j=1}^{w-1} T2_{cj}^i, T1_{cw}^i(t)\right\}}_{\substack{\text{Minimum of the specific TriCat capacity remaining.} \\ \text{OR} \\ \text{The total number of GenTre casualties present} \\ \text{for the TriCat.}}} \quad \forall i,c,w \quad (3.14)$$

Determining the Flow of Casualties That Are Sent to the Evacuation Staging Area After Receiving GenTre But Not SpecTre

The flow of $H2_{cw}$ casualties is determined by the minimal value of:

- Those who have received GenTre but not SpecTre. Make bullets .5 from left margin
- The remaining general evacuation capacity after higher priority *H2* casualties are deducted.
- The remaining specialty evacuation capacity after higher priority *H2* casualties are deducted.

Formally,

$$\underbrace{H2^{i}_{cw}(t)}_{\substack{\text{GenTre casualties}\\ \text{sent for evacuation}}} = Min\left\{\begin{array}{l} \underbrace{T1^{i}_{cw}(t)}_{\substack{\text{Those given}\\ \text{a bed for GenTre}}} - \underbrace{T2^{i}_{cw}(t)}_{\substack{\text{Those receiving}\\ \text{SpecTre}}}, \\ \underbrace{EvaCapG^{i}(t+1)}_{\substack{\text{General evacuation}\\ \text{capacity}}} - \left[\sum_{j=1}^{4}\sum_{k=1}^{w-1}\underbrace{P_{jk}H2^{i}_{jk}(t)}_{\text{All higher EvaPris}} - \sum_{j=1}^{c-1}\underbrace{P_{jw}H2^{i}_{jw}(t)}_{\substack{\text{Equivalent EvaPris}\\ \text{with higher TriCat}}}\right], \\ \underbrace{EvaCapS_{w}(t+1)}_{\substack{\text{Specific evacuation}\\ \text{capacity}}} - \underbrace{\sum_{j=1}^{c-1}H2^{i}_{jw}(t)}_{\substack{\text{GenTre treated}\\ \text{casualties}}} \end{array}\right\} \quad \forall i,c,w$$

(3.15)

<u>Determining the Flow of Casualties That Are Sent to the Staging Area After Not Receiving Any Treatment (NonTre) at the Current LOC</u>

The flow of $H1_{cw}$ casualties is determined by the minimal value of:

- Those who arrive at the MTF but do not receive GenTre.
- The remaining general evacuation capacity after the following are deducted:
  - All *H2* casualties that are evacuated as in (3.15).
  - Higher priority *H1* casualties.
- The remaining specialty evacuation capacity after the following are deducted:
  - All *H2* casualties that are evacuated as in (3.15).
  - Higher priority *H1* casualties.

Formally,

$$\underbrace{H1^{i}_{cw}(t)}_{\text{Received NonTre and sent to evac staging area.}} = Min\left\{\begin{array}{l} \underbrace{Input^{i}_{cw}(t)}_{\text{Number of each TriCat present.}} - \underbrace{T1^{i}_{cw}(t)}_{\text{Those given a bed for GenTre}}, \\ \underbrace{EvaCapG^{i}(t)}_{\text{General evacuation capacity.}} - \sum_{j=1}^{4}\sum_{k=1}^{w-1} \underbrace{P_{jk}H1^{i}_{jk}(t)}_{\text{Equivalent EvaPris that have priority.}} - \underbrace{\sum_{j=1}^{c-1} P_{jw}H1^{i}_{jw}(t)}_{\text{EvaPris with higher TriCat priority}} - \sum_{c=1}^{4}\sum_{w=1}^{4} \underbrace{P_{cw}H2^{i}_{cw}(t-1)}_{\text{GenTre casualties that being evacuated}}, \\ \underbrace{EvaCapS^{i}_{w}(t)}_{\text{Specialty evacuation capacity}} - \sum_{c=1}^{4} \underbrace{H2^{i}_{cw}(t-1)}_{\text{GenTre casualties that being evacuated}} - \sum_{j=1}^{c-1} \underbrace{H1^{i}_{jw}(t)}_{\text{EvaPris with higher TriCat priority}} \end{array}\right\} \quad \forall i,c,w$$

(3.16)

<u>Determining the Flow of Casualties Waiting for GenTre</u>

The flow of $T1Q_{cw}$ casualties is determined by the value of:

- Those who arrive at the MTF and are not sent to GenTre or the EvacStage.

$$T1Q^{i}_{cw}(t) = Input^{i}_{cw}(t) - T1^{i}_{cw}(t) - H1^{i}_{cw}(t) \tag{3.17}$$

<u>Determining the Flow of Casualties Who Have Received GenTre and are Awaiting SpecTre</u>

The flow of $T2Q_{cw}$ casualties is determined by the value of:

- Those who have received GenTre but not SpecTre and are not sent to the EvacStage.

$$T2Q^{i}_{cw}(t) = T1^{i}_{cw}(t) - T2^{i}_{cw}(t) - H2^{i}_{cw}(t) \tag{3.18}$$

<u>Determining the Flow of Casualties That are Sent to the Staging Area After Receiving Both GenTre and SpecTre</u>

The flow of $H3_{cw}$ casualties is determined by the value of:

- Those who have received SpecTre but are not RTD.

$$H3^{i}_{cw}(t) = T2^{i}_{cw}(t) - RTD^{i}_{cw}(t) \tag{3.19}$$

Determining the Flow of Casualties Being Evacuated

The flow E of casualties is determined by the sum of $H1$, $H2$ and the minimal value of:

- The number of $H3$ and HQ casualties of type (c,w) awaiting evacuation at the MASF.
- The remaining general evacuation capacity after *H1* and *H2* casualty flows are deducted.
- The remaining specialty evacuation capacity after all casualties of *H1* and *H2* plus higher priority *H3* and *HQ (*same EvaPri AND higher precedent TriCat) are deducted.

Formally,

$$\underbrace{E^i_{cw}(t)}_{\substack{\text{Evacuated}\\ \text{casualties}}} = H1^i_{cw}(t) + H2^i_{cw}(t-1) + Min\left\{\begin{array}{l} H3^i_{cw}(t-1) + HQ^i_{cw}(t-1), \\ \underbrace{EvaCapG^i(t)}_{\substack{\text{General evacuation}\\ \text{capacity.}}} - \sum_{j=1}^{4}\sum_{k=1}^{w-1} \underbrace{P_{jk}[H3^i_{jk}(t-1) + HQ^i_{jk}(t-1)]}_{\substack{\text{Equivalent EvaPris}\\ \text{that have priority.}}} - \sum_{j=1}^{c-1} \underbrace{P_{jw}[H3^i_{jw}(t-1)}_{\substack{\text{EvaPris with higher}\\ \text{TriCat priority}}} + HQ^i_{jw}(t-1)] - \sum_{c=1}^{4}\sum_{w=1}^{4} \underbrace{P_{cw}[H2^i_{cw}(t-1) + H1^i_{cw}(t),}_{\substack{\text{Higher priority casualties}\\ \text{that being evacuated}}} \\ \underbrace{EvaCapS^i_w(t)}_{\substack{\text{Specialty evacuation}\\ \text{capacity}}} - \sum_{c=1}^{4} \underbrace{[H2^i_{cw}(t-1) + H1^i_{cw}(t)]}_{\substack{\text{Higher priority casualties}\\ \text{that being evacuated}}} - \sum_{j=1}^{c-1}\sum_{j=1}^{c-1} \underbrace{P_{jw}[H3^i_{jw}(t-1) + HQ^i_{jw}(t-1)]}_{\substack{\text{EvaPris with higher}\\ \text{TriCat priority}}} \end{array}\right\} \tag{3.20}$$

Determining the Flow of Casualties Waiting to be Evacuated

The flow of HQ_{cw} casualties is determined by the value of:

- Those casualties who have been sent to or delayed in the evacuation staging area and not sent to the next higher LOC.

$$\underbrace{HQ^i_{cw}(t)}_{\substack{\text{Casualties in}\\ \text{Staging Queue}}} = \underbrace{H1^i_{cw}(t)}_{\substack{\text{NonTre}\\ \text{Casualties}}} + \underbrace{H2^i_{cw}(t-1)}_{\substack{\text{GenTre}\\ \text{Casualties}}} + \underbrace{H3^i_{cw}(t-1)}_{\substack{\text{CompTre}\\ \text{Casualties}}} + \underbrace{HQ^i_{cw}(t-1)}_{\substack{\text{Casualties in}\\ \text{Staging Queue}}} - \underbrace{E^i_{cw}(t)}_{\substack{\text{Evacuated}\\ \text{Casualties}}} \quad \forall i, c, w \tag{3.21}$$

All casualties who have completed one time period of treatment at a LOC are represented in the $Exit^i_{cw}(t)$ node located in the network as exhibited by Figure 3.5.

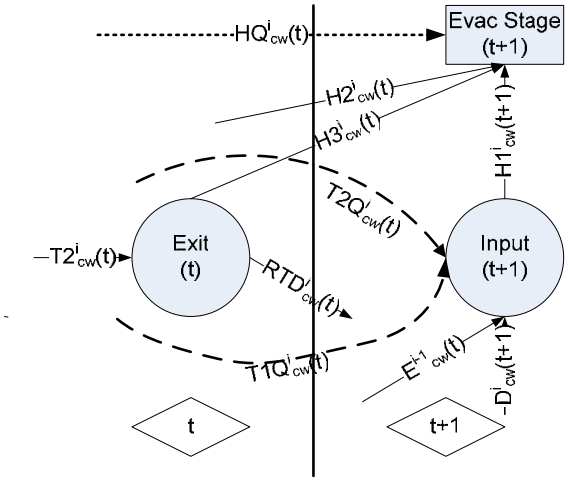

Figure 3.3 Completed Treatment Process

As before, a proportion $(\alpha^i_{cw}(t))$ of these casualties who have completed one time period of treatment will RTD while remaining casualties will automatically be staged for evacuation as represented by the arc $H3^i_{cw}(t)$ flowing from $Exit^i_{cw}(t) \rightarrow EvacStage^i_{cw}(t+1)$. Per a METCOM default policy, these casualties that have completed one time period of treatment are not bounded by the evacuation capacity nor do they reduce the capacity for the $H2^i_{cw}(t)$ GenTre flow or $H1^i_{cw}(t+1)$ NonTre flow because the latter have higher priorities. This is representative of the policy that once completed with a period of treatment the METS priority is to free up additional bed space at the MTF for treating inflow of new casualties. Thus, once completed with treatment, casualties will be sent to the evacuation staging area where they can be prioritized for evacuation.

IV. DESCRIPTIVE MODEL APPLICATION

"Victory and defeat are each of the same price."
- Thomas Jefferson

A. MEASURES OF EFFECTIVENESS (MOES):

In general, much like the theater METS policy, MOEs are selected by the SECDEF and CJCS and complied with by the COCOM and Joint Theater Surgeon (JTS). They assist in determining the appropriate prioritization and policies for treatment and evacuation timelines for casualty care and significantly impact the structural requirement of the METS. The primary MOEs associated with METCOM are developed around the ideal that optimal utilization of treatment and evacuation assets corresponds to minimal or no casualty queues. This is founded upon the notion that a casualty placed in a medical or evacuation queue is not receiving continuity of care, thus increasing the likelihood that the medical condition will exacerbate. Table 4.1 exhibits the MOEs chosen as metrics within the METCOM.

CATEGORY	EXPLANATION OF CATEGORY
1. HQ Mean	The average number of casualties delayed in the Evacuation Queue.
2. HQ Max	The maximum number of casualties for any one time period who are delayed in the Evacuation Queue.
3. T1Q Mean	The average number of casualties who while at the MTF receive no treatment and are delayed in the medical queue.
4. T1Q Max	The maximum number of casualties for any one time period who while at the MTF receive no treatment and are delayed in the treatment queue.
5. T2Q Mean	The average number of casualties who while at the MTF receive General treatment and are then delayed in the medical queue.
6. T2Q Max	The maximum number of casualties for any one time period who while at the MTF receive General treatment and are then delayed in the treatment queue.

Table 4.1 METCOM Measures of Effectiveness.

Each of these MOEs are taken over the time horizon of ten time periods (S=10). The *HQ* flow is the individual EvaPri (w=4) casualty types summed over all the TriCats, while the *T1Q* and *T2Q* are the individual TriCat (c=4) categories summed over all the EvaPris.

B. CASUALTY DISTRIBUTIONS

For comparison purposes, the implementation of METCOM also utilizes different casualty inflow distributions for each of the four policies discussed in the Chapter 3 (Treatment Priority or Evacuation Priority Policies and their two sub-policies, General and Balanced). Figure 4.1 exhibits the mean values at each time period of the four distributions utilized and are representative of different operational scenarios or individual time windows within a single operation.

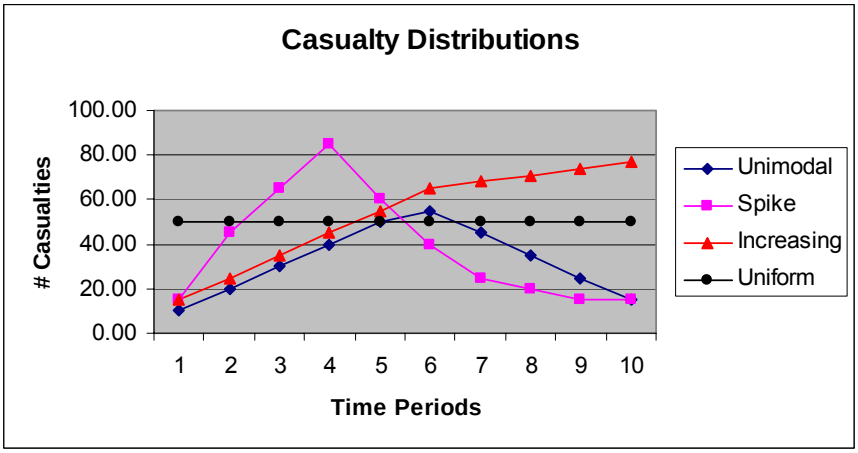

Figure 4.1 Casualty Inflow Distributions

It is assumed that casualties are correlated with combat operational intensity, thus casualties will be lower when operational intensity is low and casualties increase as the operational intensity increases. Historical analysis has exhibited this assumption holds valid due to increase in casualties caused by both battle injuries and non-battle injuries as operational tempo and intensity heightens (Leedham and Blood, 1992)

As stated, the distributions are representative of casualty flows that might be observed during specific types of combat operations or simply during certain periods of individual operations. Table 4.2 below exhibits the mean values utilized in all iterations of generating the casualty inflow values for each distribution. Additionally, Table 4.3 exhibits the actual maximum and minimum values observed for each time period over the

entire generation of values which is explained more in-depth below. Additionally, how each specific distribution was drawn and some basic assumptions on what type combat operation the distribution might reflect best are identified below.

In each distribution we have a chosen mean value for each time period. The actual inflow in each period is drawn from a normal distribution with the designated mean and standard deviation identified in the Table 4.2. Thus, the set of values for periods 1 thru 10 constitute one sample point in the analysis. This was repeated to generate 1000 sample points for each distribution of which Figure 4.1 displays its mean values. In all cases, the generated distribution values are held constant across all policy types, allowing for ease in cross comparisons.

Period	1	2	3	4	5	6	7	8	9	10
Spike Mean	15	45	65	85	60	40	25	20	15	15
Increasing Mean	15	25	35	45	55	65	68	71	74	77
Uniform Mean	50	50	50	50	50	50	50	50	50	50
Unimodal Mean	10	20	30	40	50	55	45	35	25	15
Standard Deviation: For All Distributions in Each Time Period							$\sigma = 5$			

Table 4.2 Mean Values for Each Sample Distribution (n=1000)

Period	1	2	3	4	5	6	7	8	9	10
Unimodal Distribtution										
Min	0	15	29	44	58	57	44	28	14	0
Max	32	44	62	76	99	88	79	60	45	31
Spike Distribtution										
Min	0	29	51	69	44	25	10	3	1	0
Max	30	60	80	100	76	60	43	36	37	32
Increasing Distribtution										
Min	0	11	21	32	41	49	48	55	59	61
Max	37	40	51	60	74	81	85	86	90	90
Uniform Distribtution										
Min	33	32	32	34	35	36	32	35	30	34
Max	67	64	68	67	68	69	66	67	68	67

Table 4.3 Observed Min and Max Values of Each Sample Distribution (n=1000)

Unimodal: Combat operations that are low in intensity to begin with, gradually peak to a high point and then reside back towards initial levels.

Spike: Combat operations that peak in intensity very quickly, but then quickly reside to much lower levels.

Increasing: Combat operations that gradually intensify over the entire duration of the operational time window.

Uniform: Combat operations that maintain a specific level of intensity for the entire duration.

C. APPLICATION OF THE DESCRIPTIVE METCOM MODEL

1. Assumed Parameters

For each of the models tested, multiple parameters were chosen and statically set as exhibited in Tables 4.4 thru 4.5. These parameters are user chosen and are subject to change by decision makers. However for the entirety of the METCOM descriptive model, all parameters were statically set as below.

The TriCat:EvaPri Probability matrix below in Table 4.4 exhibits the probability that each inbound casualty is assigned a specific (*c*,*w*) class designating its specific triage and evacuation priority. Again, as recent conflicts have exhibited, a majority of the traumas received by casualties are serious penetrating wounds and lacerations caused by shrapnel and gunfire (Gawande, 2004; Leedham and Blood, 1992). Thus, we assume that slightly more casualties will be of serious nature as exhibited by the highlighted quadrant of Table 4.4.

		Evacuation Priority (w)			
		w_1	w_2	w_3	w_4
Triage Category (c)	c_1	0.125	0.125	0	0
	c_2	0.125	0.125	0.1	0.1
	c_3	0	0	0.1	0.1
	c_4	0.025	0.025	0.025	0.025

Table 4.4 TriCat:EvaPri Probability Matrix

Similarly the RTD probability matrix exhibited in Table 4.5 represents the assumed probability that a casualty is able to return to duty upon completion of medical treatment. As before, it is assumed that the less severely injured of the casualties, as

exhibited in the shaded area of the table, have a much greater chance to RTD than casualties with more acute injuries.

Evacuation Priority (w)					
Triage Category (c)		w_1	w_2	w_3	w_4
	c_1	0.025	0.025	0.05	0.025
	c_2	0.025	0.025	0.15	0.20
	c_3	0.1	0.1	0.30	0.40
	c_4	0	0.025	0.025	0.025

Table 4.5 RTD Probability Matrix

The Resource Utilization Requirements parameter (P_{cw}) as exhibited in Table 4.6 indicates the amount of general evacuation capacity that a casualty of type (*c*,*w*) requires. It is representative of the fact that more severe casualties will require increased utilization of medical staff, additional patient movement items, and higher likelihood of requiring a litter or bed configuration versus a standard chair/seat within an evacuation asset. Thus, the casualties with minimal injuries are assigned a requirement of one (1), indicating they require no additional capacity other than a basic seat. However, the more severe casualties require additional capacity and thus are assigned a requirement of two (2) or three (3) resources per casualty upon the evacuation asset capacity.

Evacuation Priority (w)					
Triage Category (c)		w_1	w_2	w_3	w_4
	c_1	3	3	2	2
	c_2	3	3	2	2
	c_3	1	1	1	1
	c_4	3	3	3	3

Table 4.6 EvaCapG Resource Utilization Requirements (P_{cw})

2. Assumed Capacities

The treatment and evacuation capacities chosen for the implementation of METCOM where representative of typical Level II and Level III HSS setups that might be seen in numerous AOs. Specifically, the LOCs and their evacuation assets where designated as exhibited in Table 4.7 below.

	MEDICAL CAPABILITIES			EVACUATION ASSETS	
	OR	ICU	WARD	AMBULATORY	LITTER
LEVEL II	6	17	60	22	15
LEVEL III	12	30	96	37	24

Table 4.7 Medical and Evacuation Capacities

The Level II medical capabilities are representative of any one of the following:

- 2 Shock Trauma Platoons (STP) or
- 1 Surgical Company of the Medical Battalion, Force Service Support Group (FSSG) or
- 1 Casualty Receiving and Treatment Ship (CRTS) of LHD/LHA type.

The Level III medical capabilities are representative of an Expeditionary Medical Facility (EMF) which is typically a 1/4 to 1/3 subset of a full blown 500 bed Fleet Hospital. This is in line with the concept of keeping the LOCs mobile and minimizing their footprint within the theater of operations.

The evacuation assets are based upon the capacities of helicopters which are the preferred option for transporting casualties to CRTSs and MTFs ashore. Helicopters provide for the most rapid and least traumatic means of MEDEVAC, however, they are conducted on a “lift of opportunity” basis and are not organic or dedicated to any specific MTF (NWP 3-02.1, 1993). Therefore, it was assumed that on a best case scenario there would either be a single available helicopter or other equivalent asset available to evacuate casualties at any given time. The LOC II capacities are based upon the CH-46 helicopter capacity and the LOC III is based upon the CH-53 helicopter capacity.

Additionally, the treatment and evacuation capacities are held constant for each time period, and LOC I evacuation capacities were made extraordinarily large so that all casualty flow would automatically make it to LOC II. This allows for concentrated

analysis of LOC II and LOC III MTFs, which is where the predominant flexibility and necessitation for medical care and evacuation assets exist during forward combat operations. Specifically for this scenario, the capacities were set at the capability levels of the chosen MTF configurations for each LOC and are exhibited in Tables 4.8 and 4.9.

CAPACITY TYPE	LEVEL II CAPACITY (Beds/ORs)	LEVEL III CAPACITY (Beds/ORs)
TreCapG (General Treatment)	75	96
$TreCapS_1$ (Immediate)	6	12
$TreCapS_2$ (Urgent)	17	30
$TreCapS_3$ (Minimal)	75	96
$TreCapS_4$ (Expectant)	17	30

Table 4.8 Treatment Capacities at LOCs

General Treatment is based upon the size of medical staff and number of ward beds that each MTF has organic to it. It is assumed that the MTF can always treat casualties of the *Minimal* category up to the full bed capacity. The number of OR tables determines the number of *Immediate* type casualties that can be treated. Similarly, the number of ICU beds determines the maximum number of *Urgent* and *Expectant* casualties that can be treated.

CAPACITY TYPE	LEVEL II CAPACITY (Evac Seats)	LEVEL III CAPACITY (Evac Seats)
EvaCapG (General Evac)	22	37
$EvaCapS_1$ (Urgent)	15	24
$EvaCapS_2$ (Priority)	15	24
$EvaCapS_3$ (Routine)	22	37
$EvaCapS_4$ (Convenience)	22	37

Table 4.9 Evacuation Capacities at LOCs

General Evacuation capacity is based upon the full number of seats configured on the helicopter that casualties who are ambulatory or able to sit in an upright position may fill. The *Routine* and *Convenience* type casualties are assumed to require no special configuration and thus are only limited by the overall seat capacity of the general evacuation capacity. However, the *Urgent* and *Priority* type casualties are assumed to require being in a supine position, thus their capacities are limited by the litter configuration of the helicopter.

D. LOC II RESULTS

Results for the MOEs at LOC II are presented below. The objective is to utilize a specific casualty inflow distribution for generating 10-dimensional sample points and then to compare the various policy types across this generated sample space. In that we evaluate which policy type appears to handle a particular distribution best as exhibited in the MOEs. Tables 4.10 thru 4.21 display the mean, standard deviation, and the maximum mean value observed of the MOEs for each of the policies and their sub-policies (as explicitly described in Chapter 3) when tested over the generated 1000 sample points. Figures 4.2 thru 4.13 display the maximum MOE value observed for each policy throughout the full time horizon and over the entire sample space.

To reiterate, each sample point generates a value for the mean and maximum queue size generated over the ten time periods. The averages of these 1000 mean values exhibited are the MOE values that are displayed in the tables below. The max values contained in the figures differ from the tables in that they are a single point maximum MOE value observed over all 10 time periods and over all 1000 sample points. Together the tables and figures allow the decision maker to better discern the long run behavior and peak behavior of each queue.

Lastly, to reiterate the tracking scheme, the *HQ* flow is tracked by the EvaPri (*w*) index while the *T1Q* and *T2Q* flows are tracked by TriCat (*c*) index.

1. Increasing Distribution

a. Evacuation Queue (HQ)

Values for *HQ* are displayed in Table 4.10 and Figure 4.2. In general, the queue worsens for each policy as EvaPri becomes less of a priority. While there appears to be no standout policy, EPP-GPSP does appear to be slightly better than the rest overall

as it has the lowest mean value in three of the evacuation queue categories. Of noticeable outliers is the spike exhibited in Figure 4.2 caused in the TPP-BPSP maximum values for the *Convenience* priority casualties. However, this may be of marginal concern as these casualties realistically have minimal medical complications associated with them.

	TPP-GPSP	EPP-GPSP	TPP-BPSP	EPP-BPSP
Urgent				
Mean	2.98	2.95	1.60	1.60
Standard Deviation	0.88	0.88	0.59	0.59
Maximum	5.90	5.90	4.00	4.00
Priority				
Mean	10.79	10.74	13.20	13.20
Standard Deviation	1.64	1.62	1.50	1.50
Maximum	16.30	16.30	18.80	18.80
Routine				
Mean	19.30	18.56	19.21	19.21
Standard Deviation	3.05	2.87	2.86	2.86
Maximum	30.80	29.40	30.80	30.80
Convenience				
Mean	19.51	16.64	18.95	18.95
Standard Deviation	3.21	2.91	3.06	3.06
Maximum	31.70	26.80	31.20	31.20

Table 4.10 Mean Values of HQ at LOC II with Increasing Distribution

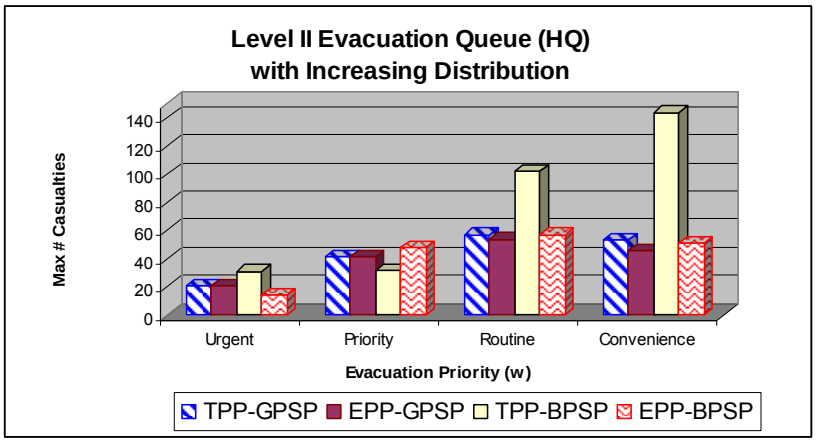

Figure 4.2 Max Values of HQ at LOC II with Increasing Distribution

b. General Treatment Queue (T1Q)

Values for *T1Q* are displayed in Table 4.11 and Figure 4.3. Again no policy appears to standout above the others. However, a general trend is obvious that while all policies treat the *Immediate* TriCat casualties better than the other TriCats, there are comparatively and significantly large queues generated for the *Urgent* category of

TriCats. As Table 4.11 exhibits, the *Urgent* category ranges from a best of mean value 11.38 to a worst of 13.5 casualties.

	TPP-GPSP	EPP-GPSP	TPP-BPSP	EPP-BPSP
Immediate				
Mean	0.00	0.00	0.01	0.00
Standard Deviation	0.00	0.00	0.00	0.00
Maximum	0.00	0.00	0.03	0.00
Urgent				
Mean	13.23	13.50	11.38	11.38
Standard Deviation	2.89	2.88	2.66	2.66
Maximum	23.00	23.40	21.00	21.00
Minimal				
Mean	12.59	13.47	11.68	11.68
Standard Deviation	2.16	2.18	2.22	2.22
Maximum	20.30	20.80	18.70	18.70
Expectant				
Mean	9.72	9.90	8.50	8.50
Standard Deviation	1.79	1.75	1.51	1.51
Maximum	13.20	13.80	12.00	12.00

Table 4.11 Mean Values of T1Q at LOC II with Increasing Distribution

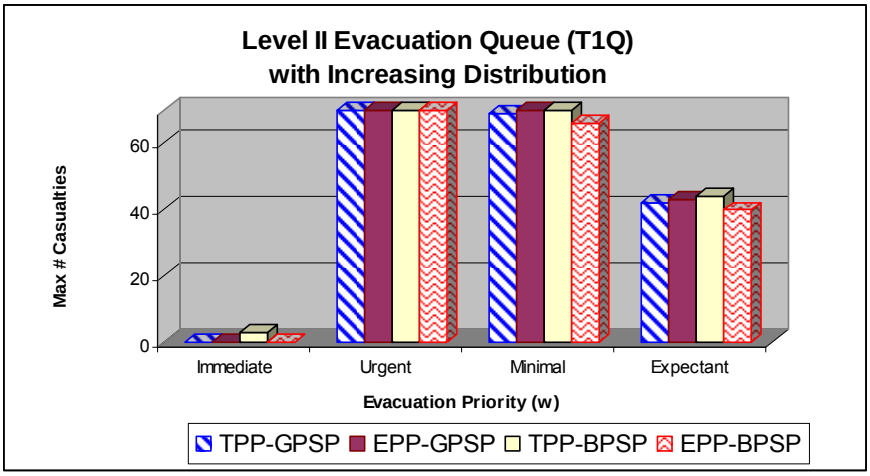

Figure 4.3 Max Values of T1Q at LOC II with Increasing Distribution

c. Specialty Treatment Queue (T2Q)

The values for *T2Q* are displayed in Table 4.12 and Figure 4.4. Overall, none of the policies performs as well in the two highest acuity TriCats as compared to the two lowest TriCats. The most obvious specific concern is the spike in maximum casualties as observed in the TPP-BPSP *Immediate* TriCat and exhibited in Figure 4.4.

	TPP-GPSP	EPP-GPSP	TPP-BPSP	EPP-BPSP
Immediate				
Mean	7.37	7.39	5.08	5.08
Standard Deviation	1.22	1.21	0.89	0.89
Maximum	11.30	11.30	8.00	8.00
Urgent				
Mean	14.42	14.66	17.25	17.25
Standard Deviation	1.18	1.16	1.21	1.21
Maximum	18.80	19.20	21.60	21.60
Minimal				
Mean	0.00	0.00	0.23	0.00
Standard Deviation	0.00	0.00	0.25	0.00
Maximum	0.00	0.00	1.10	0.00
Expectant				
Mean	0.00	0.00	0.01	0.00
Standard Deviation	0.00	0.00	0.01	0.00
Maximum	0.00	0.00	0.03	0.00

Table 4.12 Mean Values of T2Q at LOC II with Increasing Distribution

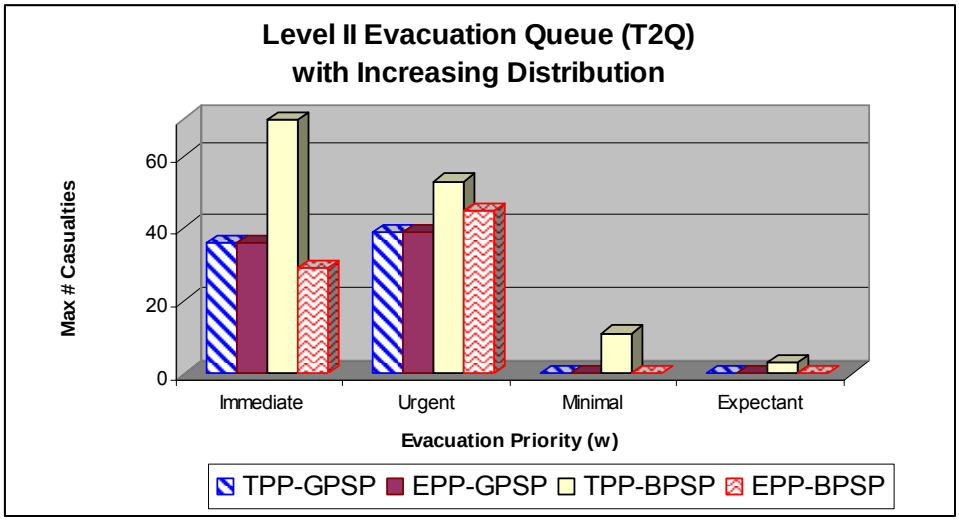

Figure 4.4 Max Values of T2Q at LOC II with Increasing Distribution

2. Unimodal Distribution

a. Evacuation Queue (HQ)

The values for *HQ* are displayed in Table 4.13 and Figure 4.5. Results for this distribution were similar to the previous distribution in that no policy was a standout best policy, but the EPP-GPSP was slightly lower for the majority of the mean queue sizes. Again like the last distribution, the TPP-BPSP produces a spike in its maximum queue size for the *Convenience* EvaPri category.

	TPP-GPSP	EPP-GPSP	TPP-BPSP	EPP-BPSP
Urgent				
Mean	3.43	3.43	6.43	1.61
Standard Deviation	1.19	1.19	1.55	0.66
Maximum	7.70	7.70	11.20	4.60
Priority				
Mean	14.38	13.80	11.34	16.83
Standard Deviation	1.76	1.78	1.77	1.69
Maximum	18.80	18.30	15.50	21.70
Routine				
Mean	19.76	18.30	19.47	19.84
Standard Deviation	2.79	2.37	2.91	2.47
Maximum	30.00	28.70	30.00	31.70
Convenience				
Mean	16.13	13.31	15.73	16.17
Standard Deviation	2.64	3.03	2.90	2.75
Maximum	25.10	21.10	56.50	25.10

Table 4.13 Mean Values of HQ at LOC II with Unimodal Distribution

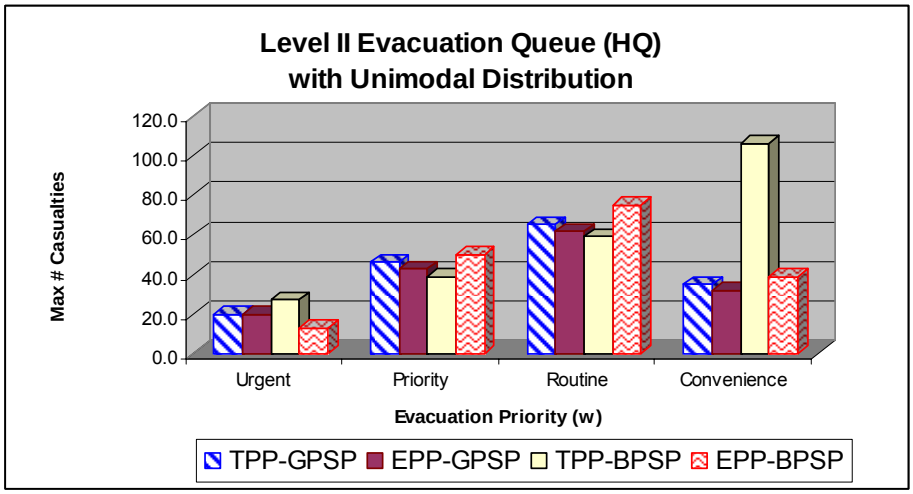

Figure 4.5 Max Values of HQ at LOC II with Unimodal Distribution

b. General Treatment Queue (T1Q)

The values for *T1Q* are displayed in Table 4.14 and Figure 4.6. This again is very similar to the Increasing distribution in that *Immediate* TriCat casualties are handled exceptionally well, but a jump in MOEs is seen in the *Urgent* TriCat casualties. Other than the *Expectant* category the two policies of EPP type appear to produce the best minimal queue sizes.

	TPP-GPSP	EPP-GPSP	TPP-BPSP	EPP-BPSP
Immediate				
Mean	0.00	0.00	0.29	0.00
Standard Deviation	0.00	0.00	0.89	0.00
Maximum	0.00	0.00	5.28	0.00
Urgent				
Mean	9.88	10.15	12.76	7.21
Standard Deviation	3.78	3.81	4.23	3.45
Maximum	24.80	24.80	28.90	20.60
Minimal				
Mean	18.86	20.09	19.89	16.96
Standard Deviation	3.58	3.61	3.60	3.49
Maximum	26.70	27.30	26.70	26.90
Expectant				
Mean	13.15	13.20	9.89	12.21
Standard Deviation	1.24	1.21	1.02	1.86
Maximum	19.60	19.60	15.00	15.40

Table 4.14 Mean Values of T1Q at LOC II with Unimodal Distribution

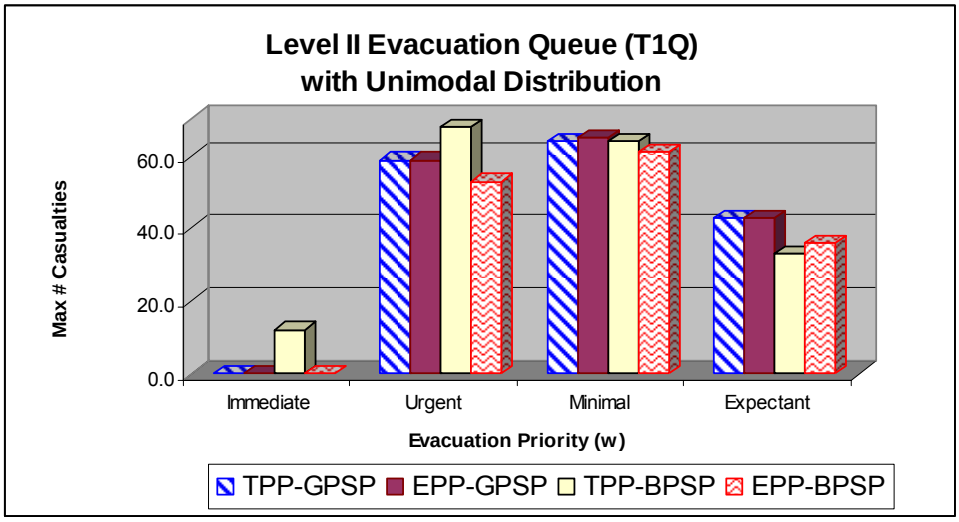

Figure 4.6 Max Values of T1Q at LOC II with Unimodal Distribution

c. Specialty Treatment Queue (T2Q)

The values for *T2Q* are displayed in Table 4.15 and Figure 4.7. Again, none of the policies performs as well in the two highest TriCats as they do for the two less acute categories. Additionally, no policy is a clear cut choice above the rest.

	TPP-GPSP	EPP-GPSP	TPP-BPSP	EPP-BPSP
Immediate				
Mean	6.60	7.65	10.63	4.41
Standard Deviation	1.48	1.57	2.36	0.90
Maximum	12.20	13.00	27.70	8.40
Urgent				
Mean	20.84	20.07	18.09	23.70
Standard Deviation	1.05	1.13	1.84	1.13
Maximum	24.00	23.20	22.10	26.30
Minimal				
Mean	0.00	0.00	0.04	0.00
Standard Deviation	0.00	0.00	0.53	0.00
Maximum	0.00	0.00	4.15	0.00
Expectant				
Mean	0.00	0.00	0.03	0.00
Standard Deviation	0.00	0.00	0.27	0.00
Maximum	0.00	0.00	1.80	0.00

Table 4.15 Mean Values of T2Q at LOC II with Unimodal Distribution

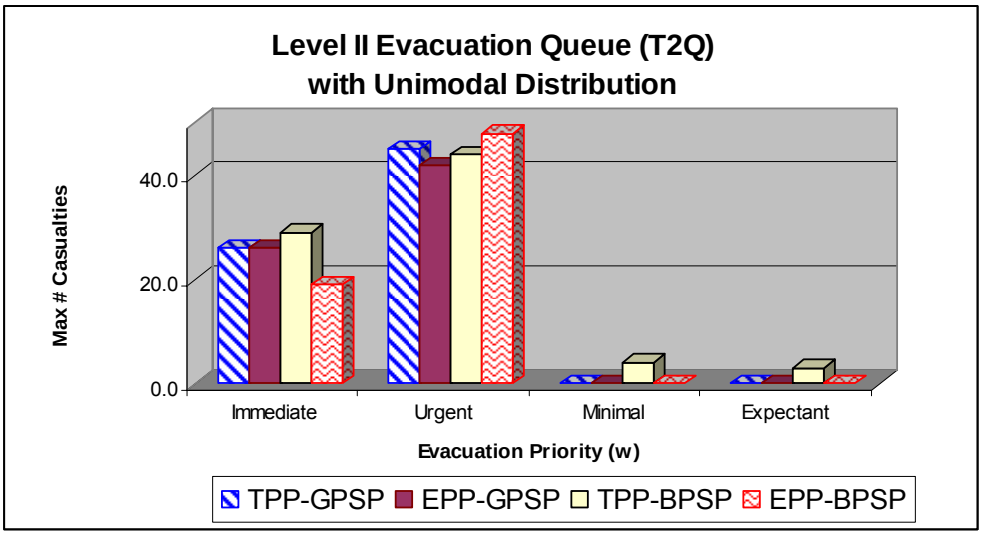

Figure 4.7 Max Values of T2Q at LOC II with Unimodal Distribution

3. Spike Distribution

a. Evacuation Queue (HQ)

The values for *HQ* are displayed in Table 4.16 and Figure 4.8. All policies are very equivalent for this queue and distribution with the EPP-GPSP appearing marginally better than the rest in 3 of the 4 TriCats. Of specific concern is that the TPP-BPSP generates spiked maximum levels as exhibited in Figure 4.8 for both the *Routine* and *Convenience* categories.

	TPP-GPSP	EPP-GPSP	TPP-BPSP	EPP-BPSP
Urgent				
Mean	2.80	2.81	1.28	1.28
Standard Deviation	0.84	0.85	0.46	0.46
Maximum	5.70	5.70	3.00	3.00
Priority				
Mean	14.80	12.26	15.45	15.45
Standard Deviation	2.00	1.56	2.04	2.04
Maximum	19.90	17.90	21.50	21.50
Routine				
Mean	25.83	24.32	27.82	27.82
Standard Deviation	2.17	2.95	2.40	2.40
Maximum	33.20	32.40	35.80	35.80
Convenience				
Mean	16.58	16.44	16.54	16.54
Standard Deviation	2.97	2.56	3.28	3.28
Maximum	26.40	25.00	28.30	28.30

Table 4.16 Mean Values of HQ at LOC II with Spike Distribution

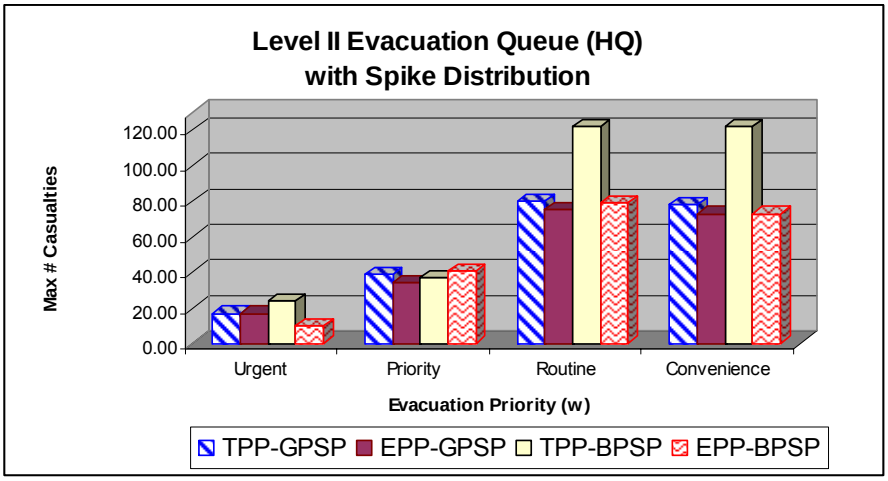

Figure 4.8 Max Values of HQ at LOC II with Spike Distribution

b. General Treatment Queue (T1Q)

The values for *T1Q* are displayed in Table 4.17 and Figure 4.9. Again the policies appear very equivalent with a slight advantage to the EPP-BPSP type in the *Urgent* and *Minimal* and *Expectant* categories.

	TPP-GPSP	EPP-GPSP	TPP-BPSP	EPP-BPSP
Immediate				
Mean	0.00	0.00	0.04	0.00
Standard Deviation	0.00	0.00	0.12	0.00
Maximum	0.00	0.00	1.41	0.00
Urgent				
Mean	3.88	3.48	2.03	2.03
Standard Deviation	2.28	2.13	1.70	1.70
Maximum	13.90	11.70	10.40	10.40
Minimal				
Mean	14.14	14.44	11.75	11.75
Standard Deviation	3.64	3.71	4.44	4.44
Maximum	27.00	27.30	26.40	26.40
Expectant				
Mean	10.60	10.58	9.42	9.42
Standard Deviation	2.66	2.54	2.42	2.42
Maximum	21.20	20.00	16.40	16.40

Table 4.17 Mean Values of T1Q at LOC II with Spike Distribution

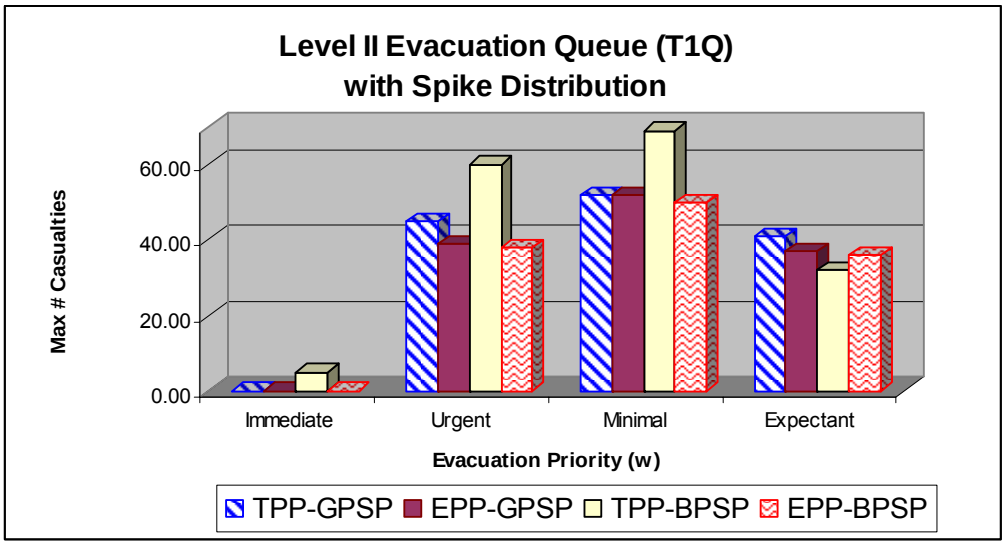

Figure 4.9 Max Values of T1Q at LOC II with Spike Distribution

c. Specialty Treatment Queue (T2Q)

The values for *T2Q* are displayed in Table 4.18 and Figure 4.10. The general trend in this queue is that the all policies except for TPP-GPSP do fair in the *Immediate* category, but comparatively poor in the *Urgent* category, and then very good for the *Minimal* and *Expectant* categories. Some concern should be concentrated on the exhibited high mean of 4.18 observed for the TPP-GPSP *Immediate* TriCat as this is

nearly three times as high as the next worst policy. It might be representative that the policies are very sensitive to the casualty flow in this category and that in an influx of casualties during the spike phase causes large queues to occur that do not subside. The TPP-GPSP policy apparently cannot overcome these queues as Figure 4.10 exhibits the overall maximum value within the TPP-GPSP *Immediate* category is almost identical to the overall queue mean of 22.00 exhibited in Table 4.18. Thus, this suggests that the maximum queue size is carried out for nearly the entire duration of the time horizon.

	TPP-GPSP	EPP-GPSP	TPP-BPSP	EPP-BPSP
Immediate				
Mean	1.01	2.08	1.90	1.90
Standard Deviation	0.96	1.28	1.11	1.11
Maximum	6.30	7.10	5.80	5.80
Urgent				
Mean	24.43	21.72	25.48	25.48
Standard Deviation	6.05	3.99	4.92	4.92
Maximum	35.90	31.20	36.70	36.70
Minimal				
Mean	0.00	0.00	0.22	0.00
Standard Deviation	0.00	0.00	0.23	0.00
Maximum	0.00	0.00	1.93	0.00
Expectant				
Mean	0.00	0.00	0.02	0.00
Standard Deviation	0.00	0.00	0.01	0.00
Maximum	0.00	0.00	0.03	0.00

Table 4.18 Mean Values of T2Q at LOC II with Spike Distribution

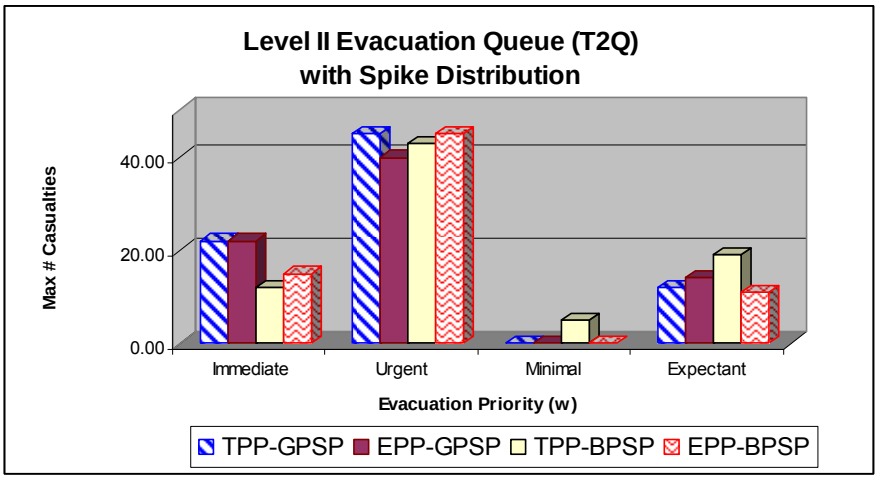

Figure 4.10 Max Values of T2Q at LOC II with Spike Distribution

4. Uniform Distribution

a. Evacuation Queue (HQ)

The values for *HQ* are displayed in Table 4.19 and Figure 4.11. In general the policies are very equivalent, but it should be noted that each policy gets worse (queue sizes increase) as EvaPri lessens for the first three categories.

	TPP-GPSP	EPP-GPSP	TPP-BPSP	EPP-BPSP
Urgent				
Mean	0.08	0.07	0.05	0.05
Standard Deviation	0.20	0.18	0.14	0.14
Maximum	1.70	1.60	1.50	1.50
Priority				
Mean	21.51	16.74	20.71	20.71
Standard Deviation	3.24	2.62	3.35	3.35
Maximum	29.30	25.90	31.30	31.30
Routine				
Mean	41.41	42.75	44.85	44.85
Standard Deviation	2.92	3.76	2.82	2.82
Maximum	46.10	49.80	49.70	49.70
Convenience				
Mean	25.42	27.83	24.76	24.76
Standard Deviation	5.51	3.52	3.62	3.62
Maximum	40.50	39.20	37.70	37.70

Table 4.19 Mean Values of HQ at LOC II with Uniform Distribution

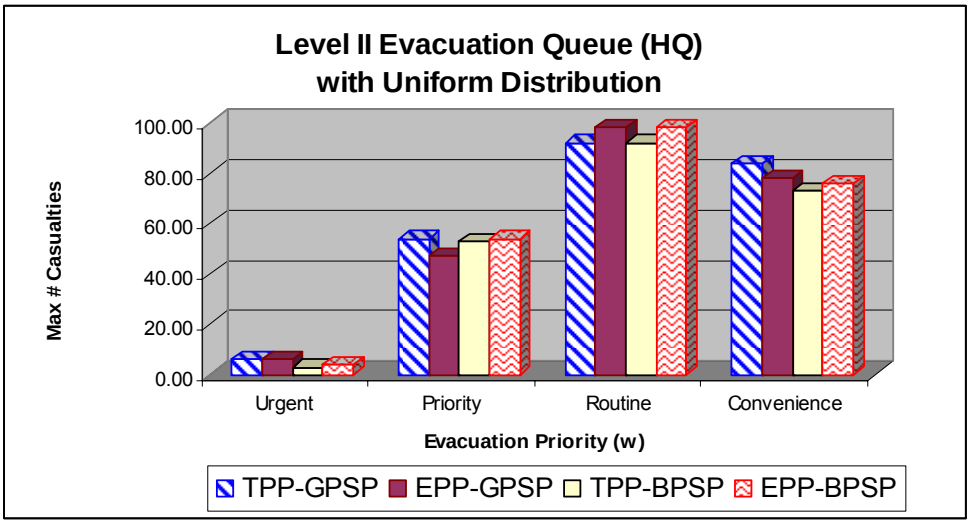

Figure 4.11 Max Values of HQ at LOC II with Uniform Distribution

b. General Treatment Queue (T1Q)

The values for *T1Q* are displayed in Table 4.20 and Figure 4.12. Similar to the evacuation queue, each policy worsens during the first three EvaPris. It appears that the EPP-GPSP is marginally the best policy while the TPP-GPSP type appears to be the worst.

	TPP-GPSP	EPP-GPSP	TPP-BPSP	EPP-BPSP
Immediate				
Mean	0.00	0.00	0.04	0.00
Standard Deviation	0.00	0.00	0.12	0.00
Maximum	0.00	0.00	1.41	0.00
Urgent				
Mean	3.88	3.48	2.03	2.03
Standard Deviation	2.28	2.13	1.70	1.70
Maximum	13.90	11.70	10.40	10.40
Minimal				
Mean	14.14	14.44	11.75	11.75
Standard Deviation	3.64	3.71	4.44	4.44
Maximum	27.00	27.30	26.40	26.40
Expectant				
Mean	10.60	10.58	9.42	9.42
Standard Deviation	2.66	2.54	2.42	2.42
Maximum	21.20	20.00	16.40	16.40

Table 4.20 Mean Values of T1Q at LOC II with Uniform Distribution

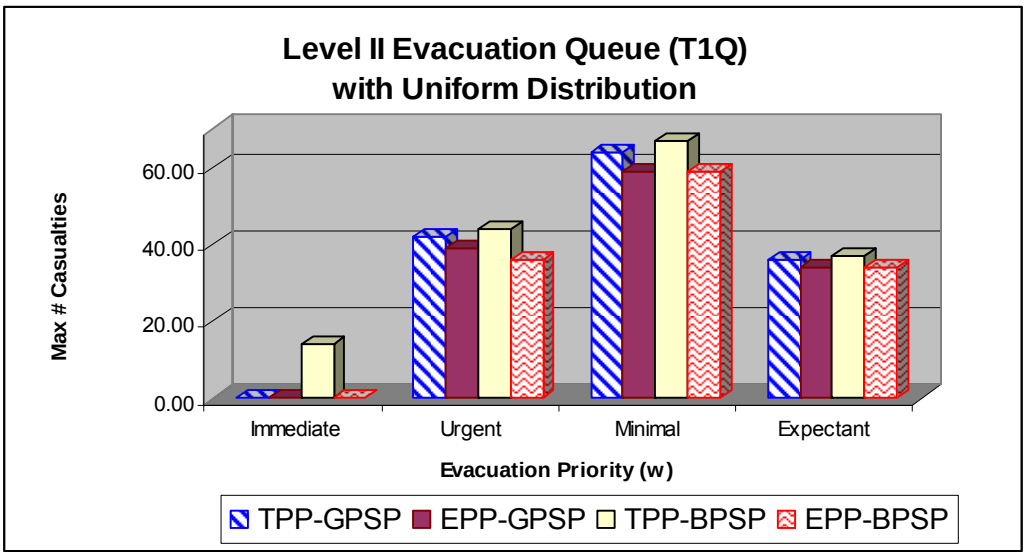

Figure 4.12 Max Values of T1Q at LOC II with Uniform Distribution

c. *Specialty Treatment Queue (T2Q)*

The values for *T2Q* are displayed in Table 4.21 and Figure 4.13. Similar to the other distributions, every policy shows a large spike in queue size for the *Urgent* category comparative to the other TriCats. In general, no policy is a clear standout above the others for this queue and distribution.

	TPP-GPSP	EPP-GPSP	TPP-BPSP	EPP-BPSP
Immediate				
Mean	1.01	2.08	1.90	1.90
Standard Deviation	0.96	1.28	1.11	1.11
Maximum	6.30	7.10	5.80	5.80
Urgent				
Mean	24.43	21.72	25.48	25.48
Standard Deviation	6.05	3.99	4.92	4.92
Maximum	35.90	31.20	36.70	36.70
Minimal				
Mean	0.00	0.00	0.00	0.00
Standard Deviation	0.00	0.00	0.00	0.00
Maximum	0.00	0.00	0.00	0.00
Expectant				
Mean	0.00	0.00	0.00	0.00
Standard Deviation	0.00	0.00	0.00	0.00
Maximum	0.00	0.00	0.00	0.00

Table 4.21 Mean Values of T2Q at LOC II with Uniform Distribution

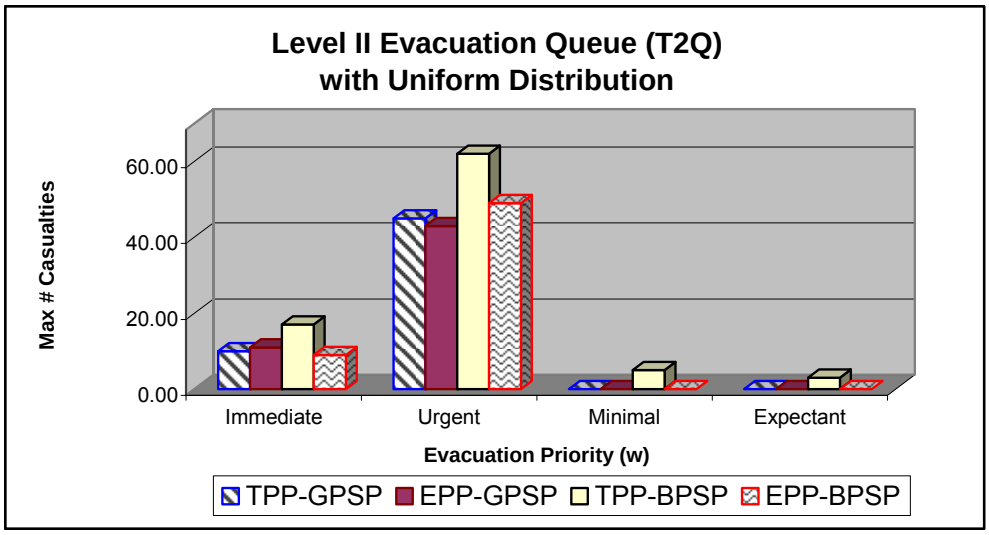

Figure 4.13 Max Values of T2Q at LOC II with Uniform Distribution

5. LOC II General Conclusions

While no policy appeared as a clear cut choice for any of the distributions, the two that stood out as marginally better at the more acute categories (c = 1,2 or w = 1,2) were the EPP-BPSP and EPP-GPSP. The worst overall policy appeared to be the TPP-BPSP type as it produced multiple significant spikes within the *HQ* for the *Convenience* category and less often but still large spikes for the *Routine* category. Large spikes are not desired, and thus the TPP-BPSP plan is not recommended for use in some distributions.

What was also discernable was that there consistently appeared to be a general trend that all policies could handle the *Immediate/Urgent* (TriCat/EvaPri) casualty capacities better than they could the *Urgent/Priority* (TriCat/EvaPri) casualty capacities. As the ICU beds are the main linkage to the available medical capacities to the *Urgent* category casualties, it may be prudent to consider an increase in this specific medical capability if reduction in *T1Q* and *T2Q* sizes is warranted.

This pattern also suggests that the current evacuation capacities are in general capable of evacuating the *Urgent* EvaPris within acceptable levels but at the cost of utilizing a large majority of the evacuation capacity available. Therefore the lower priority EvaPris have such reduced capacity to compete for evacuation, that it reflects in much higher *HQ* means for EvaPris such as the Priority category.

E. LOC III RESULTS

While LOC II results were quite enlightening the LOC III findings were that the current treatment and evacuation capacities were quite sufficient to cause no queues to be formed. However, several key takeaways can be noted from these type results. First it would be beneficial to model the distributions again with higher mean values to see how LOC III capabilities do function when throughput of casualties to them is constraining to either medical and/or evacuation capacities. Then, similar results and analysis could be determined on the effectiveness of policies with the LOC III much as they were in the LOC II MTFs.

Additionally, this lends well to the optimization analysis done in the following chapter. With no queues produced, it suggests that the LOC III capacities are

underutilized and there may be extensive waste of resources. Thus, it is valuable to discern how much capacities can be reduced at LOC III and still functionally meet the objective of producing minimal or no queue sizes. This will relate the range of sensitivity the system has to volume of casualties and the medical and evacuation capacities. It will also assist in identifying resources that are not necessary at the MTF thereby allowing for reallocation of them to another asset or purely cutting them out to save costs.

V. METCOM OPTIMIZATION CAPABILITY

"The very first requirement in a hospital is that it should do the sick no harm."
- Florence Nightingale

A. CAPABILITIES OPTIMIZATION MODEL

Dependent upon the cost and operational constraints emplaced upon the METS, decision makers can utilize results from the descriptive model to supplement both micro or macro adjustments to METS policy or capacities in order to better meet the identified MOEs. However, METCOM offers also the ability for optimizing the METS structure subject to medical responsiveness and cost requirements. METCOM is easily adjusted to addresses the following optimization problems:

1) Minimize the cost of medical capabilities subject to satisfying certain MOE and capacity constraints.

2) Minimize an MOE (e.g., queue size) subject to capacity and budget constraints.

These additional modeling initiatives will be discussed and applied to scenarios in the next section. However, the basic formulation of the optimization model is as follows:

Optimization Model

Indices

t - Time period	where $t = 1 \ldots T$
i - Medical level of care (LOC)	where $i = 1,\ldots,5$
c – Triage category of casualty (TriCat)	where $c = 1,\ldots,4$
w – Evacuation priority category (EvaPri)	where $w = 1,\ldots,4$

c,w – Designated class of a casualty inclusive of their unique TriCat and EvaPri

Parameters

S Number of time periods of the operation (Time Horizon).

$d_{cw}(t)$ Number of new combat casualties of class (c,w) at time period t.

$UHQ_w^i(t)$ Upper bound on evacuation queue size of casualties in EvaPri w at LOC i and at time period t (Decision maker requirement).

$UT1Q^i(t)$ Upper bound on general treatment queue size of casualties in EvaPri w at LOC i and at time period t (Decision maker requirement).

$UT2Q_c^i(t)$ Upper bound on specialty treatment queue size of casualties in EvaPri w at LOC i and at time period t (Decision maker requirement).

$TMAX^i(t)$ Maximum possible general capacity at LOC i at time period t.

$TMAX_c^i(t)$ Maximum possible specialty capacity for casualty type c at LOC i at time period t.

$EMAX^i(t)$ Maximum evacuation capacity allowable at LOC i and at time period t.

$EMAX_w^i(t)$ Maximum evacuation capacity allowable for priority type w at LOC i and at time period t.

CT_c Cost of delivering one unit of specialty medical treatment capacity for casualty type c.

CT_G Cost of delivering one unit of general medical treatment capacity for any type casualty.

CE_w Cost of delivering one unit of specialty evacuation capacity for casualty of priority w.

CE_G Cost of delivering one unit of general evacuation capacity for casualty of priority *w*.

P_{cw} The general evacuation capacity resources required by a single casualty of class (*c*,*w*).

$\alpha^i_{cw}(t)$ Proportion of class (*c*,*w*) casualties at level of care *i* that receive completed treatment and are returned to duty in time period *t*.

<u>Decision Variables</u>

$TreCapG^i(t)$ General treatment capacity at level of care *i* in period *t*.

$TreCapS^i_c(t)$ Specialty treatment capacity of Type *c* casualty at level of care *i* in time period *t*.

$EvaCapG^i(t)$ General evacuation capacity at level of care *i* in period *t*.

$EvaCapS^i_w(t)$ Evacuation capacity of Type *w* priority at level of care *i* in time period *t*.

<u>Computational Variables</u>:

$T1^i_{cw}(t)$ Number of casualties in class (*c,w)* at LOC *i* receiving General Treatment (GenTre) in bed at the MTF during time period *t*.

$T2^i_{cw}(t)$ Number of casualties in class (*c*,*w*) at LOC *i* receiving Specialty Treatment of type *c* (SpecTre_c) in bed at the MTF during time period *t*.

$T1Q^i_{cw}(t)$ Number of casualties of in class (*c*,*w*) at LOC *i* having received Non-Treatment (NonTre) and delayed in queue during time period *t*. This queue is labeled NonTre queue.

$T2Q^i_{cw}(t)$ Number of casualties in class (*c*,*w*) at LOC *i* having received GenTre in bed and then delayed in queue prior to SpecTre during time period *t*. This queue is labeled GenTre queue.

$H1^i_{cw}(t)$ Number of casualties in class (c,w) at LOC i having received no treatment (NonTre) at this level and sent to evacuation staging in time period t.

$H2^i_{cw}(t)$ Number of casualties in class (c,w) at LOC i having received GenTre in bed and sent to evacuation staging in time period t+1 before receiving SpecTre_c.

$H3^i_{cw}(t)$ Number of casualties in class (c,w) at LOC i having received complete treatment (CompTre) during time period t and are sent to evacuation staging in time period t+1.

$HQ^i_{cw}(t)$ Number of casualties in class (c,w) at LOC i during period t being delayed in an evacuation queue.

$E^i_{cw}(t)$ Number of casualties in class (c,w) at LOC i being evacuated to level of care i + 1 during time period t.

$RTD^i_{cw}(t)$ Number of casualties in class (c,w) at LOC i who are Returned to Duty during time period t.

Following is the formulation for Problem Statement 1: Minimize the cost of medical capabilities subject to satisfying certain MOE and capacity constraints.

<u>Formulation</u>

$$\text{Min} \quad \sum_{\text{i}} \left[\sum_{c} CT_c TreCapS^i_c + CT_G TreCapG^i + \sum_{w} CE_w EvaCapS^i_w + CE_G EvaCapG^i \right] \qquad (5.1)$$

It is assumed that the available capacities for both treatment and evacuation hold constant throughout the given time horizon of the model.

s.t.

Balance Constraints

The balance of flow at an *Input* node is:

$$E_{cw}(t-1)^{*} + T1Q^{i}_{cw}(t-1) + T2Q^{i}_{cw}(t-1) - H1^{i}_{cw}(t) - T1Q^{i}_{cw}(t) - T2Q^{i}_{cw}(t-1) = 0 \qquad (5.2)$$

The balance of flow at an *Intermed* node is:

$$T1^{i}_{cw}(t) - H2^{i}_{cw}(t) - T2Q^{i}_{cw}(t) - T2^{i}_{cw}(t) = 0 \qquad (5.3)$$

The balance of flow at an *Exit* node is:

$$T2^{i}_{cw}(t) - H3^{i}_{cw}(t) - RTD^{i}_{cw}(t)^{**} = 0 \qquad (5.4)$$

The balance of flow at an *Evac Stage* node is:

$$H1^{i}_{cw}(t) + H2^{i}_{cw}(t-1) + H3^{i}_{cw}(t-1) + HQ^{i}_{cw}(t-1) - HQ^{i}_{cw}(t) - E^{i}_{cw}(t) = 0 \qquad (5.5)$$

* At LOC I, this term is replaced by the inflow of new combat casualties, $d_{cw}(t)$

** $RTD^{i}_{cw}(t) = \alpha_{cw} T2^{i}_{cw}(t)$

Capacity Constraints

The total number of casualties who may receive GenTre must be less than the general treatment capacity of LOC *i* at time period *t*.

$$\sum_{c}\sum_{w} T1^{i}_{cw}(t) - TreCapG^{i}(t) \le 0 \quad \forall i \qquad (5.6)$$

The numbers of casualties in TriCat who may receive SpecTre must be less than the specialty treatment capacity of LOC *i* at time period *t*.

$$\sum_{w} T2^{i}_{cw}(t) - TreCapS^{i}_{c}(t) \le 0 \quad \forall i \qquad (5.7)$$

The total number of casualties who may be evacuated must require equal or less evacuation resources than allowed within the general evacuation capacity of LOC *i* at time period *t*.

$$\sum_{c}\sum_{w} P_{cw} E^{i}_{cw}(t) - EvaCapG^{i}(t) \le 0 \quad \forall i \qquad (5.8)$$

The number of casualties in EvaPri who may be evacuated must be less than the specialty evacuation capacity of LOC *i* at time period *t*.

$$\sum_{c} E_{cw}^{i}(t) - EvaCapS_{w}^{i}(t) \leq 0 \quad \forall i \tag{5.9}$$

The resources required for the combined specialty evacuation capacities must be equal or less than the general evacuation capacity in LOC *i* at time period *t*.

$$\sum_{w} P_{cw} EvaCapS_{w}^{i} - EvaCapG^{i} \leq 0 \quad \forall i \tag{5.10}$$

Constraints 5.11 and 5.12 coincide with the joint doctrine that states, "Each succeeding level [LOC] possesses the same treatment capabilities as those forward of it (NTTP 4-02.2, 2001)." This same doctrine is assumed to hold as well for evacuation capabilities as represented in constraints 5.13 and 5.14. Additionally, the capacities must be bound as exhibited in constraints 5.15 thru 5.18 by some upper limit representing the realization that expansion of capabilities is not limitless and is constrained by available resources.

The specialty treatment capacity at higher LOCs must be equal or greater than that same specialty treatment capacity at a lower LOC at time period *t*.

$$TreCapS_{c}^{i} - TreCapS_{c}^{i+1} \leq 0 \quad \forall i \tag{5.11}$$

The general treatment capacity at higher LOCs must be equal or greater than the general treatment capacity at a lower LOC at time period *t*.

$$TreCapG^{i} - TreCapG^{i+1} \leq 0 \quad \forall i \tag{5.12}$$

The specialty evacuation capacity at higher LOCs must be equal or greater than that same specialty evacuation treatment capacity at a lower LOC at time period *t*.

$$EvaCapS_{w}^{i} - EvaCapS_{w}^{i+1} \leq 0 \quad \forall i \tag{5.13}$$

The general evacuation capacity at higher LOCs must be equal or greater than the general evacuation capacity at a lower LOC at time period *t*.

$$EvaCapG^{i} - EvaCapG^{i+1} \leq 0 \quad \forall i \tag{5.14}$$

The general treatment capacity at LOC *i* must be lower than some upper bound at time period *t.*

$$TreCapG^{i}(t) \leq TMAX^{i}(t) \quad \forall i \tag{5.15}$$

The specialty treatment capacity at LOC *i* must be lower than some upper bound at time period *t.*

$$TreCapS_{c}^{i}(t) \leq TMAX_{c}^{i}(t) \quad \forall i \tag{5.16}$$

The general evacuation capacity at LOC *i* must be lower than some upper bound at time period *t.*

$$EvaCapG^{i}(t) \leq EMAX^{i}(t) \quad \forall i \tag{5.17}$$

The specialty evacuation capacity at LOC *i* must be lower than some upper bound at time period *t.*

$$EvaCapS_{w}^{i} \leq EMAX_{w}^{i}(t) \quad \forall i \tag{5.18}$$

Constraints 5.19 thru 5.21 represent the decision makers' selection of acceptable risk and inefficiency of the METS within the METCOM. These constraints indicate the maximum queue size acceptable in the treatment and evacuation processes. Again, as queues represent a discontinuity of care, allowing higher upper bounds constitutes an accepted increase risk in the morbidity and mortality rates of casualties being treated in the HSS system.

The allowable evacuation queue size at LOC *i* must be lower than some upper bound at time period *t.*

$$\sum_{c} HQ_{cw}^{i}(t) \leq UHQ_{w}^{i}(t) \quad \forall i \tag{5.19}$$

The allowable general treatment queue size at LOC *i* must be lower than some upper bound at time period *t.*

$$\sum_{c,w} T1Q_{cw}^{i}(t) \leq UT1Q^{i}(t) \quad \forall i \tag{5.20}$$

The allowable specialty treatment queue size at LOC *i* must be lower than some upper bound at time period *t*.

$$\sum_{w} T2Q_{cw}^{i}(t) \le UT2Q_{c}^{i} \qquad \forall i \tag{5.21}$$

$$TreCapG^{i}, TreCapS_{c}^{i}, EvaCapG^{i}, EvaCapS_{w}^{i} = \text{int} \tag{5.22}$$

$$TreCapG^{i}, TreCapS_{c}^{i}, EvaCapG^{i}, EvaCapS_{w}^{i} \ge 0 \qquad \forall i \tag{5.23}$$

B. ASSUMPTIONS

Similar to the descriptive model, we must make several assumptions about the associated variables and parameters. Both are purely user chosen and may be set at any range of different values to reflect decision makers desires for more lax or more stringent requirements. Table 5.1 exhibits the selected costs (CT_c, CT_G, CE_w, CE_G) associated with delivery medical general and specialty treatment. A baseline cost is assigned to the general treatment capacity and then the cost for specialty treatment is derived from this. Here, we assume that casualties of type *Immediate* cost twice as much per casualty treated as the general treatment did. The remaining specialty capacity costs are assigned according to the expected resource utilization levels they demand above the general treatment capacity.

CAPACITY TYPE	LEVEL II COSTS	LEVEL III COSTS
TreCapG (General Treatment)	2	2
$TreCapS_1$ (Immediate)	4	4
$TreCapS_2$ (Urgent)	3	3
$TreCapS_3$ (Minimal)	2	2
$TreCapS_4$ (Expectant)	3	3

Table 5.1 Treatment Costs of Providing One Unit of Capacity

Table 5.2 exhibits the selected costs (CE_w, CE_G) associated with evacuating capacities. In this scenario we assume that evacuation capacity costs are uniformly twice as much as the associated treatment capacities. Thus, all figures are doubled from the previous table, however, this does not affect the evacuation capacities proportionality to one another.

CAPACITY TYPE	LEVEL II COSTS	LEVEL III COSTS
EvaCapG (General Evac)	4	4
$EvaCapS_1$ (Urgent)	8	8
$EvaCapS_2$ (Priority)	6	6
$EvaCapS_3$ (Routine)	4	4
$EvaCapS_4$ (Convenience)	6	6

Table 5.2 Evacuation Costs of Providing One Unit of Capacity

The constraints on the maximum allowable evacuation and treatment queue sizes (*UHQ, UT1Q, and UT2Q*) were set as exhibited in Table 5.3 below. For this scenario, it was assumed that queues were not acceptable for the most acute casualties (c=1,2 or w=1,2) and thus the maximum queue size of each were set to zero.

	LEVEL II MAXIMUM QUEUE SIZE	LEVEL III MAXIMUM QUEUE SIZE
HQ Urgent	0	0
HQ Priority	0	0
HQ Routine	11	18
HQ Convenience	11	18
T1Q Immediate	0	0
T1Q Urgent	0	0
T1Q Minimal	8	10
T1Q Expectant	5	9
T21Q Immediate	0	0
T2Q Urgent	0	0
T2Q Minimal	8	10
T2Q Expectant	5	9

Table 5.3 Maximum Allowable Queue Size

The non-zero values for maximum queue sizes exhibited in Table 5.3 were set as follows for i = 2 and 3 (LOC II and LOC III);

$UHQ_w^i \quad (w = 3,4)$: At 50% of the ambulatory evacuation capacity set at LOC II and III respectively.

$UT1Q_c^i$ & $UT2Q_c^i$ (c=3): At 10% of the treatment capacity for *Minimal* TriCats set at LOC II and III respectively.

$UT1Q_c^i$ & $UT2Q_c^i$ (c=4): At 30% of the treatment capacity for *Expectant* TriCats set at LOC II and III respectively.

Again, these can be set at any range of values to reflect the planners' and decision makers' objectives.

C. CASUALTY INFLOW

With the preceding assumptions made, METCOM was tested with the TPP-GPSP policy utilized in the descriptive model. For equivalency in comparison the same Uniform distribution with $\mu = 50$ was utilized as the base for inflow of casualties. Due to modeling limitations, σ was set at 0, thereby causing exactly 50 casualties to enter the system each time period.

D. RESULTS

Table 5.4 below exhibits the treatment capacities of the default METS and then after the optimization model has been applied.

Most notable is that there appears plentiful capacities in most cases, allowing for quite significant reductions in actual required capacity to meet all constraints. The most heavily laden capacities to meet casualty demand appear in LOC II for the *Urgent* and *Minimal* casualty types, with capacity actually requiring increasing for the former of the two. This is indicative of what is somewhat expected as the more acute TriCats require greater utilization of ORs and ICU beds which are costly and difficult for the current LOC II MTFs to maintain given their goal maximum mobility and minimum footprint in theater.

CAPACITY TYPE	LEVEL II CAPACITY DEFAULT	LEVEL II CAPACITY OPTIMIZED	LEVEL III CAPACITY DEFAULT	LEVEL III CAPACITY OPTIMIZED
TreCapG (General Treatment)	75	25	96	31
$TreCapS_1$ (Immediate)	6	9	12	7
$TreCapS_2$ (Urgent)	17	17	30	16
$TreCapS_3$ (Minimal)	75	0	96	5
$TreCapS_4$ (Expectant)	17	2	30	0

Table 5.4 Default and Optimized Treatment Capacities for TPP-GPSP Policy

Table 5.5 below exhibits the evacuation capacities of the default METS and then after the optimization model has been applied. Similar to the treatment capacities, the most acute evacuation categories of *Urgent* and *Priority* require at least if not more capacity than what is currently offered at LOC II. The model also exhibits that while LOC III capacities appear more than adequate, the LOC II evacuation assets are almost at maximum capacity for their general capacity and most acute casualties.

CAPACITY TYPE	LEVEL II CAPACITY DEFAULT	LEVEL II CAPACITY OPTIMIZED	LEVEL III CAPACITY DEFAULT	LEVEL III CAPACITY OPTIMIZED
EvaCapG (General Evac)	22	19	37	3
$EvaCapS_1$ (Urgent)	15	16	24	12
$EvaCapS_2$ (Priority)	15	15	24	9
$EvaCapS_3$ (Routine)	22	5	37	0
$EvaCapS_4$ (Convenience)	22	8	37	0

Table 5.5 Default and Optimized Evacuation Capacities for TPP-GPSP Policy

The actual optimization of cost in this scenario is exhibited in Table 5.6 and represents a 34% cost reduction.

	OBJECTIVE FUNCTION VALUE
Default Capacity	1240
Optimized Capacity	815

Table 5.6 Objective Function Values

E. DISCUSSION

The optimization model highlights many key factors, probably the most important of which may be that we have significant over-allocation of resources in some treatment and evacuation capacities. Caution must be advised here though, as this is specific to the chosen distribution, assumptions, and time horizon chosen for the model. However, it does give us particularly good insight upon how well the current assets and policy would function and potentially more important, what cost is required to meet the needs.

By identifying the capacity requirements, METCOM also presents further insight into how unmet capacities can be addressed. For example, we indicated that *Immediate* and *Urgent* capacities in LOC II were fully utilized or unmet by the default MTF capabilities. By knowing how much need is unmet, decision makers can make a sound decision on how to resolve the issue. For small unmet needs, planners may wish to simply or increase the assets at the MTF to accommodate the requirement. This might not be the case if large unmet needs materialize as increasing the size of the MTF too much conflicts with the objective of forward deployed MTFs maintaining mobility and a small footprint in theater. Thus, the need might warrant employing an additional LOC II MTF within the AO in order to supplement the needed capacities, but still maintain the advantages of individually small and mobile units.

VI. CONCLUSIONS AND RECOMMENDATIONS

> *"Pay every attention to the sick and wounded. Sacrifice your baggage, everything for them. Let the wagons be devoted to their use, and if necessary your own saddles."*
>
> -Napoleon I[4]

A. CONCLUSIONS

Probably one of the most challenging aspects to the METS is the dynamic environment in which it must operate and the shear magnitude of unknowns caused by the "Fog of War". The number of variables effecting both treatment and evacuation can at times be staggering. As Kott (1999) states, "New patient requests come in; others get canceled…availability of key assets is subject to unpredictable events…and even weather can require a mission be delayed, rerouted, or canceled." Thus, it is paramount to have powerful yet realistic modeling techniques and tools to account for such variability and complexities within the medical and evacuation system. METCOM accomplishes this by adding clarity of analysis through defined MOEs that aide decision makers in assessing the ramifications of policy and structural makeup of the HSS delivery system. Additionally, METCOM can address the cost associated with delivery of care and evacuation, allowing again for decision makers to meet all requirements at the minimal cost. Taken together, the descriptive and optimization data that METCOM provides can be utilized by planners and decision makers to employ appropriate policies, insert necessary medical and evacuation capabilities within, and economize the cost so that unneeded resources may allocated elsewhere.

Utilization of METCOM is most warranted in conjunction with other planning and analysis tools such as TML+ and MAT. Together, they can provide the type of definitive qualitative and quantitative data that can clarify, validate, and support decision makers' choices for policy implementation and capacity capabilities that best meet the objective of saving lives and mitigating injury and morbidity of the warfighters.

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4 As cited in Chandler, David G. The Military Maxims of Napoleon New York; Macmillan; 1997.

B. RECOMMENDATIONS FOR FUTURE RESEARCH

While illuminating in many ways, this is but a glimpse of the construct and processes of the military HSS system and METS capabilities. While the purpose of the research was to provide a balance of descriptive and prescriptive analysis, it is by no means encompasses the entirety of complexities and variability within the METS. Numerous opportunities to expand and modify METCOM exist and include some of the following:

METCOM did not limit nor consider the time in system of casualties when prioritizing their medical treatment or evacuation. Thus, technically a casualty could remain stuck in a queue for multiple periods due to their inability to be prioritized over other casualties of greater TriCat or EvaPri competing for the same capacities. It would be beneficial to incorporate a tracking index that would associate an increasing cost parameter for the greater amount of time a specific casualty remains in the system.

It is also recommended that follow-on studies increase the breadth of the research by incorporating patient condition (PC) codes that expand the limited class (c,w) casualties into more specific acuity and anatomical region of injury. Currently, well over 400 PCs exist, but when categorized into anatomical region, can be aggregated into a few dozen groupings. This would potentially lend to better prioritization of the absolute most acute casualties and also assist in identifying at a more precise level any gaps or delays that existed in accommodating special patient treatment or evacuation demands.

Similarly, METCOM does not differentiate between causation of injury for any of the casualties. Modeling whether injuries are due to being wounded in action (WIA), disease (DIS), or non-battle injury (NBI), could enhance the identification of required capacities and assist in building a prioritization policy necessary to address the situation. For example, resources required to treat multiple diseased patients could vary drastically from much of the blunt trauma expected with NBI or the acute lacerations and shrapnel wounds expected in WIA casualties.

METCOM could also be modified with additional stressors to the efficient operation of the system by making the capacities dynamic rather than static during the time horizon of the model. Particularly as evacuation capacity is dependent upon mostly

lifts of opportunity and operational availability of air and ground evacuation assets, modeling a capacity with moderate variability would again add realism to the scenario. A final stressor of the METS that could be added is the addition of enemy prisoners of war (EPWs), and non-combatant casualties to the population that requires treatment and/or evacuation. Not only would this add overall casualty volume to the system, it could represent significant resource utilization. EPWs require additional escort personnel, thereby potentially reducing available medical staff and always reducing evacuation capacity to accommodate the physical presence of Military Police (MP) or non-medical Retained Personnel (RP). Noncombatants can cause other concerns, particularly when pediatric patients begin to fill the system. Not only can they be overwhelming to the limited pediatric specialists in a theater of operations, but they may raise additional ethical, moral, and emotional considerations when deciding prioritization of (c,w) class as compared to an adult service member or even EPW of the same (c,w) class.

Thus, it is obvious that the research contained herein is but a scratch of the surface on the topic of modeling and optimizing the METS. This topic will continue to be at the forefront of Naval operational concerns, particularly with the evolving changes in LOC II structures and capabilities along with the future vision of performing all LOC III care from a seabasing asset (Medial Seabasing, 2005). Therefore, the requirements for quality planning aides and tools such as TML+, MAT, and METCOM will continue to be of greatest necessity to assist decision makers in formulating optimal choices within the complex arena of operational plan.

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APPENDIX A

TRIAGE CASUALTY CATEGORIES		
Group	**Type**	**Description**
C_1	Immediate Treatment	The immediate treatment group includes patients requiring emergency life-saving surgery. These procedures should not be time consuming and should concern only those patients with high chances for survival such as respiratory obstruction, accessible hemorrhage, and emergency amputation.
C_2	Delayed Treatment	The delayed treatment group includes patients badly in need of time-consuming major surgery, but whose general condition permits delay in surgical treatment without unduly endangering life. To mitigate the often critical effects of delay in surgery, sustaining treatment, such as stabilizing IV fluids, splinting, administering antibiotics, performing catheterization and gastric decompression, and relieving pain, will be required. Examples are large muscle wounds, fractures of major bones, intra-abdominal and/or thoracic, head or spinal injuries, and uncomplicated major burns.
C_3	Minimal Treatment	The minimal treatment group includes patients with relatively minor injuries who can effectively care for themselves or receive care from untrained personnel. Examples include minor lacerations, abrasions, fractures of small bones and minor burns.
C_4	Expectant	The expectant treatment group comprises patients having serious and often multiple injuries, requiring time consuming and complicated treatment with a low chance of survival. If fully treated, these patients may make heavy demands on medical manpower and supplies. Until the mass casualty situation is under control, they will receive appropriate supportive treatment. The extent of treatment depends on available supplies and manpower and may involve the use of large doses of analgesics. These patients should not be abandoned and every effort made for their comfort. The possibility of their survival, despite alarming injuries, must always be considered. Examples include severe multiple injuries, severe head or spinal injuries, large doses of radiation, and widespread severe burns.
C_5	Deceased	This group is comprised of the killed in action (KIA) and died of wounds received in action (DWRIA). They are the last category of patients and will be handled by Graves Registration, if established. However, in the absence of established graves registration, TF supply personnel will be responsible for the Mortuary Affairs Program. Master at Arms and Chaplains will assist in the initial phase of handling this category of patients.

Triage Categories From NTTP 4-02.2, NWP 4-02.

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APPENDIX B

Multicommodity Computational Arc Flow for Descriptive METS:

$$\underbrace{T1^{i}_{cw}(t)}_{\text{GenTre casualties}} = \underbrace{Input^{i}_{cw}(t)}_{\text{Inflow of casualties at MTF}} - \underbrace{T1Q^{i}_{cw}(t)}_{\text{NonTre queue}} - \underbrace{H1^{i}_{cw}(t)}_{\text{NonTre casualties and sent to evac staging area}} \qquad \begin{array}{l} i = 1,\ldots,5 \\ c = 1,\ldots,4 \end{array} \tag{6.1}$$

$$\underbrace{T2^{i}_{cw}(t)}_{\text{Casualties receiving SpecTre}} = \underbrace{Intermed^{i}_{cw}(t)}_{\text{In bed casualties who've received GenTre}} - \underbrace{T2Q^{i}_{cw}(t)}_{\text{GenTre queue}} - \underbrace{H2^{i}_{cw}(t)}_{\text{Casualties with GenTre and sent to evac staging area}} \qquad \begin{array}{l} i = 1,\ldots,5 \\ c = 1,\ldots,4 \end{array} \tag{6.2}$$

$$\underbrace{RTD^{i}_{cw}(t)}_{\text{Those returned to duty after completed treatment.}} = \underbrace{\alpha^{i}_{cw}(t)}_{\text{RTD proportion matrix.}} \times \underbrace{T2^{i}_{cw}(t)}_{\text{Those who have completed treatment in period t.}} \qquad \begin{array}{l} i = 1,\ldots,5 \\ c = 1,\ldots,4 \end{array} \tag{6.3}$$

$$\underbrace{H3^{i}_{cw}(t)}_{\text{Completed treatment and sent to evac staging area.}} = \underbrace{T2^{i}_{cw}(t)}_{\text{Completed treatment.}} - \underbrace{RTD^{i}_{cw}(t)}_{\text{Completed treatment and returned to duty.}} \qquad \begin{array}{l} i = 1,\ldots,5 \\ c = 1,\ldots,4 \end{array} \tag{6.4}$$

$$\underbrace{E^{i}_{cw}(t)}_{\text{Casualties evacuated to level i+1}} = \underbrace{EvacStage^{i}_{cw}(t)}_{\text{Evac Stage Area}} - \underbrace{HQ^{i}_{cw}(t)}_{\text{Casualties in staging queue}} \qquad \begin{array}{l} i = 1,\ldots,5 \\ w = 1,\ldots,4 \end{array} \tag{6.5}$$

$$\underbrace{HQ^{i}_{cw}(t)}_{\text{Casualties in staging queue}} = \underbrace{EvacStage^{i}_{cw}(t)}_{\text{Evac Stage Area}} - \underbrace{E^{i}_{cw}(t)}_{\text{Casualties evacuated to level i+1}} \qquad \begin{array}{l} i = 1,\ldots,5 \\ w = 1,\ldots,4 \end{array} \tag{6.6}$$

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